Assessment of river discharge changes in the Indochina Peninsula region under a changing climate(Dissertation_全文)

AUTHOR(S):

Duong Duc Toan

Assessment of river discharge changes in the Indochina Peninsula region under a changing climate

Duong Duc Toan

2014

Assessment of river discharge changes in the Indochina Peninsula region under a changing climate

by

Duong Duc Toan

A dissertation

submitted in partial fulfillment of the requirement

for the degree of Doctor of Philosophy

Dept. of Civil and Earth Resources Engineering

Kyoto University, Japan

2014

Abstract

River discharge is a key variable of the hydrological cycle. It integrates all the processes occurring within a river basin (e.g., runoff and evapotranspiration). Statistical properties of river discharge are seen as an indicator for climate change because they reflect changes in precipitation and evapotranspiration. Therefore, good estimates of future river discharge are very important for water resources assessment and water-related disaster management.

Currently, general circulation models or global climate models (GCMs) are the most promising tools to project future changes and associated impacts in the hydrological cycle. They have been used to estimate various climatological variables (e.g., temperature, precipitation, evaporation, or runoff) which are very important to evaluate the impacts of climate change on hydrology and water resources. Projection of river discharge under climate change is generally taken by driving a hydrological model with outputs from GCMs.

In the Indochina Peninsula region, the average surface temperature showed an increase of about 0.6 to 1.0 degree Celsius over the last century according to the latest assessment report of the Intergovernmental Panel on Climate Change (IPCC). The region is likely to suffer more from climate change based on the increasing frequency and intensity of extreme weather events such as floods, droughts, and tropical cyclones. Therefore, an assessment of potential future changes in river discharge in the Indochina Peninsula region is essential.

This thesis focuses on projection of river discharge in the region under a changing climate using flow routing model 1K-FRM and runoff generation data from the super-high-resolution atmospheric general circulation model MRI-AGCM3.2S which was jointly developed by Meteorological Research Institute (MRI) and Japan Meteorological Agency (JMA) for three climate experiments: the present climate (1979-2008), the near future climate (2015-2044) and the future climate (2075-2104). The potential future changes in river discharge in the Indochina Peninsula region were examined by comparing projected river discharge in the near future and future climate experiments to the one in the present climate experiment. The statistical analysis of river discharge changes in the region was carried out to locate possible hotspot basins with significant changes related to floods, droughts or water resources. The uncertainties in the future climate projections were also evaluated using different ensemble experiments from MRI-AGCM and MIROC5 datasets. Bias correction of runoff generation data was considered to improve river discharge projection using output of the land surface process model SiBUC.

The increase of flood risk was found in the Irrawaddy River basin (Myanmar) and Red River basin (Vietnam). The risk of droughts tended to increase in the middle part of Mekong River basin (Lao PDR) and in the central and southern part of Vietnam. The statistical significance of future changes in river discharge in the Indochina Peninsula region was also detected in the Irrawaddy River basin, the upper most part of the Salween and the Mekong River basin, and in the central part of Vietnam. In addition, the uncertainty in river discharge projection arising from the differences in cumulus convection schemes and spatial resolution was found much larger than the uncertainty sourced from changing sea surface temperature patterns. Land surface process model SiBUC also showed a good performance in reproducing runoff generation data. However, further works should be done in bias correction of runoff generation data to improve river discharge projection.

Keywords: river discharge projection, statistical significance, MRI-AGCM3.2S, 1K-FRM, bias correction.

Declaration of authorship

I declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research with the exception of any work of others which has all been appropriate referenced. It has not been submitted, either in part or whole, for a degree at this or any other university.

Acknowledgements

This thesis was completed in the Laboratory of Hydrology and Water Resources Research, Department of Civil and Earth Resources Engineering, Graduate School of Engineering, Kyoto University under a full-time PhD course with the guidance of Prof. Yasuto Tachikawa. It has been more improved thanks to the comments and suggestions from examination committee members, Prof. Eiichi Nakakita and Assoc. Prof. Sunmin Kim.

I would like to express my sincere gratitude to my supervisor, Prof. Yasuto Tachikawa, for his immense knowledge, excellent guidance, and valuable suggestions throughout this research work. I would have never been able to accomplish my thesis without his kind supervision, support, and encouragement.

I would like to acknowledge Prof. Michiharu Shiiba, Assist. Prof. Kazuaki Yorozu, Assoc. Prof. Sunmin Kim, and other professors in Kyoto University for their valuable guidance, comments, and suggestions to improve my research.

I also wish to show my great appreciation to all my family members, especially my parents and my wife, for their endless support and encouragement.

I would like to say thanks to Water Resources University and Ministry of Education and Training of Vietnam for giving me a chance to take this PhD course at Kyoto University and providing financial support.

Last but not least, special thanks to all my friends, my colleagues, my lab members and other people who helped me and shared both good time and hard time together during my study in Kyoto University.

Table of contents

List of figures

List of tables

Chapter 1

Introduction

1.1 Background

Water is an essential resource necessary for human survival, sustaining economic development and the functioning of the ecosystem. Water cycle or hydrologic cycle on the Earth has a close relationship to climate. It links water resources and climate and plays an important role in the climate system. Water resources are also very sensitive to climate change. As changes in global climate occur, they are likely to intensify hydrologic cycle and have significant impacts on hydrology and water resources.

According to the latest report on climate change published by the Intergovernmental Panel on Climate Change (IPCC) in 2013, Climate change 2013: The Physical Science Basis, the term "climate change" is defined as follows:

> *"Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use."* (Hartmann et al., 2013)

Climate change is now widely accepted as a scientific fact. In the report, IPCC confirmed that warming in the climate system is incontrovertible. Many observed changes in the climate system, such as warming of the atmosphere, diminishing snow and ice, rising sea levels, are unprecedented over decades to millennia (Hartmann et al., 2013). It is believed that climate change is mainly caused by greenhouse gas emissions from human activities including industrial processes, fossil fuel combustion and deforestation.

IPCC also reported that the global average surface temperature has increased about 0.89 degree Celsius over the period 1901-2012 and about 0.72 degree Celsius over the period 1951-2012 (Hartmann et al., 2013). In the Indochina Peninsula region, observation data also showed an increase of about 0.6 to 1.0 degree Celsius over the last century. This warming of global climate has caused a number of changes in hydrological systems: changed precipitation patterns, increased frequency and intensity of extreme weather events such as heavy rainfall, typhoons, floods, and droughts. The confidence level of these findings, which were assessed probabilistically using observations, is from medium to very high.

These changes in global climate will change the hydrologic cycle including the distribution, variability and trends of rainfall, runoff, and evaporation. The redistribution and changes of water resources could pose a serious threat to human society and environment, especially for the developing region like the Indochina Peninsula. Therefore, an assessment of potential future changes and impacts of global warming on water resources is urgently required. It will help decision makers to develop appropriate mitigation and adaptation strategies for climate change.

In climate change research, besides long term observations, general circulation models or global climate models (GCMs) have been the most promising tools to project future changes and associated impacts in the hydrologic cycle. GCMs stand for general circulation models because they simulate the circulation of the atmosphere. They are fully three-dimensional global models that attempt to simulate climate and climate change using numerical weather prediction techniques. GCMs represent climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes (Hartmann et al., 2013). They have been used to estimate various climatological variables (e.g., temperature, precipitation, evaporation or runoff) which are very important to evaluate the impacts of climate change on hydrology and water resources.

GCMs currently provide the most comprehensive method to investigate the physical and dynamical processes of the atmosphere system. However, it is difficult to make reliable projections of regional hydrological changes directly from GCMs due to the coarse spatial resolution. They include representation of hydrological cycle and resolve the overall water balance but do not provide sufficient details to address impacts of climate change on hydrology and water resources (Graham et al., 2007). To simulate the regional hydrological impacts of climate change, the most widely used approach is to combine the outputs of GCMs with a conceptual or physically-based hydrological model. There are several advantages of using regional hydrological models for assessing the impacts of climate change on water resources: easier to manipulate and faster to operate than GCMs; can be used at various spatial scales and dominant process representations; flexible in identifying and selecting suitable approaches to evaluate any specific region; can be tailored to fit the characteristics of available data (Xu, 1999).

In order to assess the climate change impacts on hydrology and water resources, projection of river discharge is necessary because it is a key variable of the hydrological cycle. River discharge integrates all the processes occurring within a river basin (e.g., runoff and evapotranspiration). Statistical properties of river discharge are seen as an indicator for climate change because they reflect changes in precipitation and evapotranspiration. Thus, good estimates of future river discharge are very important for water resources assessment and water-related disaster management.

Projection of river discharge under a changing climate is generally taken by driving a hydrological model with outputs from GCMs under different emission scenarios. This approach has been used in the climate change impact assessment of hydrological systems at different scales: global scales (e.g., Weiland et al., 2012; Hirabayashi et al., 2008; Nohara et al., 2006), regional or national scales (e.g., Sato et al., 2013; Thompson et al., 2013), and basin scales (e.g., Hunukumbura et al., 2012; Jiang et al., 2007; Thodsen, 2007).

On the other hand, results from climate change impact studies are often subject to uncertainties because GCMs cannot fully describe the system. For most of the climate change projections, the dominant uncertainties come from boundary condition and initial condition uncertainty, model structure and parameters of GCMs (Knutti, 2008). By intercomparing and evaluating GCMs participating in the Coupled Model Intercomparison Project (CMIP), Lambert and Boer (2001) found that an equally weighted average of several coupled climate models is usually agree better with observations than any single model. And Hageman et al. (2011) confirmed that simulation of river runoff for most selected catchments in the study were improved with the usage of bias-corrected GCM data. Therefore, a multi-model ensemble of GCMs together with bias-correction methods is usually used to obtain a reliable impression of the climate change and provide uncertainty information.

1.2 Research Objectives

This study focuses on analyzing the changes in river discharge in the Indochina Peninsula region under a changing climate. Detailed objectives of this study as follows:

- ♦ To project river discharge in the Indochina Peninsula region using a distributed flow routing model and outputs from general circulation models.
- ♦ To examine potential changes in river discharge in the region under a changing climate.
- ♦ To analyze the statistical significance of river discharge changes in the Indochina Peninsula region to locate possible hotspot basins where significant changes related to floods, droughts or water resources could occur.
- ♦ To evaluate the uncertainties in the future climate projections by comparing simulations using ensemble experiments of different GCMs.

♦ To improve future projection of river discharge by applying bias correction to GCM runoff generation data.

1.3 Thesis outline

This thesis consists of 7 chapters discussing the relative change in river discharge in the Indochina Peninsula region under a changing climate, the statistical significance of river discharge changes, the uncertainty in the future climate projections in the region, and bias corrections of GCM runoff generation data.

In chapter 2, information about the study area and data used in this study including topographic data, general circulation data, and distributed flow routing model are described.

Chapter 3 presents projection of river discharge in the Indochina Peninsula region using a distributed flow routing model named 1K-FRM and runoff generation data from GCM jointly developed by the Japan Meteorological Agency and Meteorological Research Institute (MRI-AGCM). In this chapter, the simulated river discharge for three climate experiments (the present climate, the near future climate, and the future climate) were compared to examine the changes in river discharge in the region (Duong et al., 2013).

Chapter 4 describes the statistical tests for significance of projected river discharge changes in the Indochina Peninsula region. The Shapiro-Wilk test was selected to test for normality of projected river discharge data. Then, the parametric Welch correction t-test or the non-parametric Mann-Whitney U test was applied to test for statistical significance of river discharge changes based on the results of normality test (Duong et al., 2014b).

Chapter 5 presents the comparison of projected river discharge and statistical significance of changes between simulations using runoff generation data from ensemble experiments of different GCMs to evaluate the uncertainties in the future climate projections (Duong et al., 2014a).

Bias corrections of runoff generation data to improve future river discharge projection are discussed in chapter 6. Land surface process model Simple Biosphere including Urban Canopy (SiBUC) is applied to simulate runoff data using JRA-55 reanalysis data and satellite data (e.g., soil data and vegetation data). Runoff generation data from SiBUC model are considered as reference data to correct biases in GCMs' outputs. Biases between GCM runoff generation data and reference runoff data are corrected using quantile-quantile mapping bias correction method. Then, the corrected runoff generation data are used as input for flow routing model 1K-FRM to investigate the future changes in river discharge.

The last chapter, chapter 7, summaries the study with conclusions and remarks.

References

Arora, V.K.: Streamflow simulations for continental-scale river basins in a global atmospheric general circulation model (2001) *Advances in Water Resources*, 24, 775–791.

Duong, D. T., Tachikawa, Y., Shiiba, M., Yorozu, K. (2013) River discharge projection in Indochina Peninsula under a changing climate using the MRI-AGCM3.2S dataset. *Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, Vol. 69, No. 4, I_37-I_42.

Duong, D. T., Tachikawa, Y., Yorozu, K. (2014a) Changes in river discharge in the Indochina Peninsula region projected using MRI-AGCM and MIROC5 datasets. *Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, Vol. 70, No. 4, I_115-I_120.

Duong, D. T., Tachikawa, Shiiba, M., Yorozu, K. (2014b) Statisitcal analysis of river discharge projected using the MRI-AGCM3.2S dataset in Indochina Peninsula. *Hydrology in a Changing World: Environmental and Human Dimensions*, IAHS Publ. 363, 165-170.

Graham L. P, Hagemann S., Jaun S., and Beniston M. (2007) On interpreting hydrological change from regional climate models. *Climatic Change*, 81, 97-122.

Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J.

Soden, P.W. Thorne, M. Wild and P.M. Zhai (2013) Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.*

Hunukumbura, P. B., Tachikawa, Y. (2012) River discharge projection under climate change in the Chao Phraya river basin, Thailand, using the MRI-GCM3.1S dataset, *Journal of the Meteorological Society of Japan*, 90A, 137 – 150.

IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, 1535 pp.

Jiang, T., Chen, D.Y.Q., Xu, C.Y. (2007) Comparison of hydrological impacts of climate change simulated by six hydrological models in the Dongjiang Basin, South China. *Journal of Hydrology*, 336, 316-333.

Knutti, R. (2008) Should we believe model predictions of future climate change? *Phil. Trans. R. Soc. A.*, 366, 4647-4664.

Lambert, S. J, Boer, G. J. (2001) CMIP1 evaluation and intercomparison of coupled climate models. *Clim. Dynam.*, 17, 83-106.

Nohara, Daisuke, Akio Kitoh, Masahiro Hosaka, Taikan Oki (2006) Impact of Climate Change on River Discharge Projected by Multimodel Ensemble. *J. Hydrometeor*, 7, 1076–1089.

Raisanen, J. (2007) How reliable are climate models?. *Tellus.* 59A, 2-29.

Sato, Y., Kojiri, T., Michihiro, Y., Suzuki, Y. and Nakakita, E. (2013) Assessment of climate change impacts on river discharge in Japan using the super-high-resolution MRI-AGCM. *Hydrol. Process.*, 27, 3264–3279.

Sperna Weiland, F. C., van Beek, L. P. H., Kwadijk, J. C. J., and Bierkens, M. F. P. (2012) Global patterns of change in discharge regimes for 2100. *Hydrol. Earth Syst. Sci.*, 16, 1047-1062.

Xu, C. Y.: Climate change and hydrologic models (1999) A review of existing gaps and recent research evelopments. *Water Resources Management*, 13(5), 369–382.

Chapter 2

Study area, input data and hydrological model

2.1 Study area

The study site is the Indochina Peninsula, a region in Southeast Asia, which covers from latitude 5°N to 34°N and from longitude 91°E to 109.5°E. The coverage was shown in Fig. 2.1. It lies roughly southwest of China and east of India. In this area, the whole country of Vietnam, Laos, Cambodia, Thailand, Myanmar and some parts of China are belonged.

Fig. 2.1 Map of the study area (source: Encyclopedia Britannica, Inc.)

The Indochina Peninsula region is located in an area affected by the Southeast Asian monsoon system. It is also affected by the changes from inter-annual climate system over the Pacific and Indian Oceans, which causes precipitation and temperature anomalies over this area directly, or coupling with a monsoon event.

There are five large river basins in this area including the Mekong River basin, Irrawaddy River basin, Salween River basin, Chao Phraya River basin, and Red River basin. The square measures of the Mekong, Irrawaddy, Salween, Chao Phraya, and Red River basins are about 814,000, 425,000, 330,000, 178,000 and 170,000 km^2, respectively.

2.2 Hydrological model

The hydrological model used in this study is a distributed flow routing model named 1K-FRM which was developed by Hydrology and Water Resources Research Laboratory of Kyoto University (http://hywr.kuciv.kyoto-u.ac.jp/products/1K-DHM/1K -DHM.html). 1K-FRM is a distributed flow routing model based on kinematic wave theory.

2.2.1 Catchment model

1K-FRM was based on a catchment topography model. The catchment model was developed using Digital Elevation Models. The flow direction is defined using 8-direction method, which assigns flow from each grid cell to one of its 8 neighbours, either adjacent or diagonally, in the direction with the steepest downward slope as illustrated in Fig 2.2.

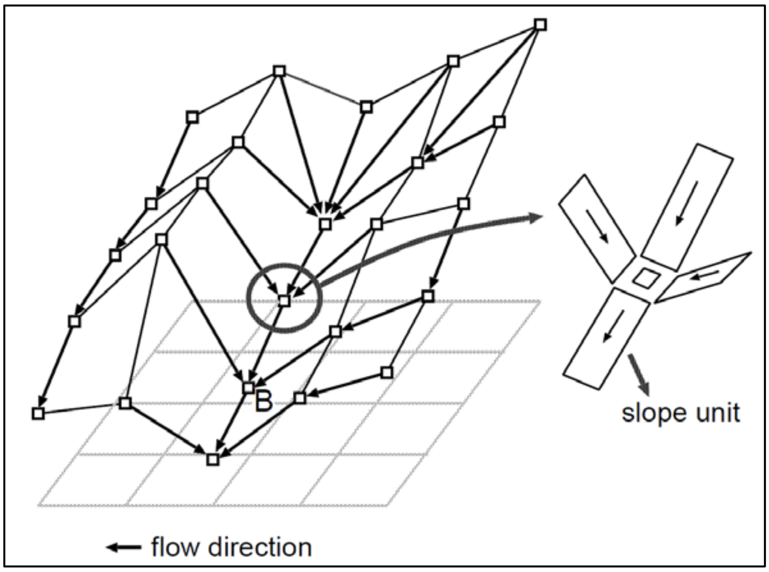


Fig. 2.2 Schematic drawing of a catchment model using a DEM

(Arrows in the figure show the flow of discharge on the slope or river unit)

Each slope element determined by the flow direction is represented by a rectangle formed by the two adjacent nodes of grid cells. Catchment topography is represented by a set of slope units. For each slope unit, its area, length and gradient used for a flow model are easily calculated. Then the runoff is routed according to the flow direction information applying the kinematic wave flow model to all slope elements.

The topographic information used for 1K-FRM in this study (e.g., elevation, flow direction, flow accumulation) was generated from processing the scale-free global streamflow network dataset, which provided by Masutani et al. (2006) with a spatial resolution of 5-arc-minute.

2.2.2 Flow model

1K-FRM is a distributed flow routing model based on kinematic wave theory. The kinematic wave model is applied to all rectangular elements to route the water to downstream according to the derived catchment model.

The basic form of kinematic wave equation for each rectangular slope elements is:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q_L(x,t) \qquad (1)$$

where t is time; x is distance; A is cross-sectional area; Q is discharge; and $q_L(x,t)$ is the lateral inflow per unit length of each slope element.

The Manning type relation of the discharge and the cross-sectional area as follows:

$$Q=\alpha A^m,\ \alpha=\frac{\sqrt{i_0}}{n}\left(\frac{1}{B}\right)^{m-1},\ m=\frac{5}{3} \qquad (2)$$

where i_0 is the slope; n is the Manning roughness coefficient; and B is the width of the flow.

Equation (2) is derived from Manning’s or Chezy’s laws which are flow resistance laws of open channel uniform flow. It is combined with the continuity equation to route the water.

2.3 Topographic data

In general, the selection of Digital Elevation Model (DEM) resolution for simulation applications depends on many factors such as scale of the processes being modelled, numerical simulation approach and specific topographic parameters that are to be extracted from the DEM. Moreover, the selection of DEM resolution for a particular application is often driven by data availability, purpose of the research, and computational resources. For hydrological models which are grid based, topographic parameters (e.g., elevation, river length, flow direction) and simulation processes are determined at every grid cell. So, the data volume and computational resources are proportional to the number of grid cells which themselves increase quadratically for each doubling of the horizontal spatial resolution. As a result, finer spatial resolution grids require higher computational resources.

The original topographic data used in flow routing model 1K-FRM is Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales (HydroSHEDS; Lehner, 2006) with spatial resolution of 1-km. However, for a large study area as the Indochina Peninsula region, using 1-km spatial resolution topographic data is not suitable considering the requirement of computational resources and long simulation time. Therefore, to ensure the balance of spatial resolution, computational resources, and application of flow routing model for climate change research with large study area. A method to process scale-free topographic information data for flow routing model 1K-FRM from scale-free global stream-flow network data set was proposed. Masutani et al. (2006) developed a scale-free global stream-flow network creation method as the basis of basin-wide hydrologic analyses for any integrated river basins. The most important advantage of this method is to conserve fundamental hydraulic information based on the finest-resolution stream-flow channel network, on any spatial scale. They provided a dataset of stream-flow networks with 11 different scales from high resolution (3s ≈ 90 meters, 6s, 9s, 12s, 15s), medium resolution (30s, 1 min, 2 min, 3 min), to low resolution (5 min, 10 min ≈ 20 km). And it enables hydrological models independent of spatial resolution. However, the dataset consists of topographic data of individual river basins. Fig. 2.3 shows river basins in the Indochina Peninsula region from the scale-free stream-flow network dataset

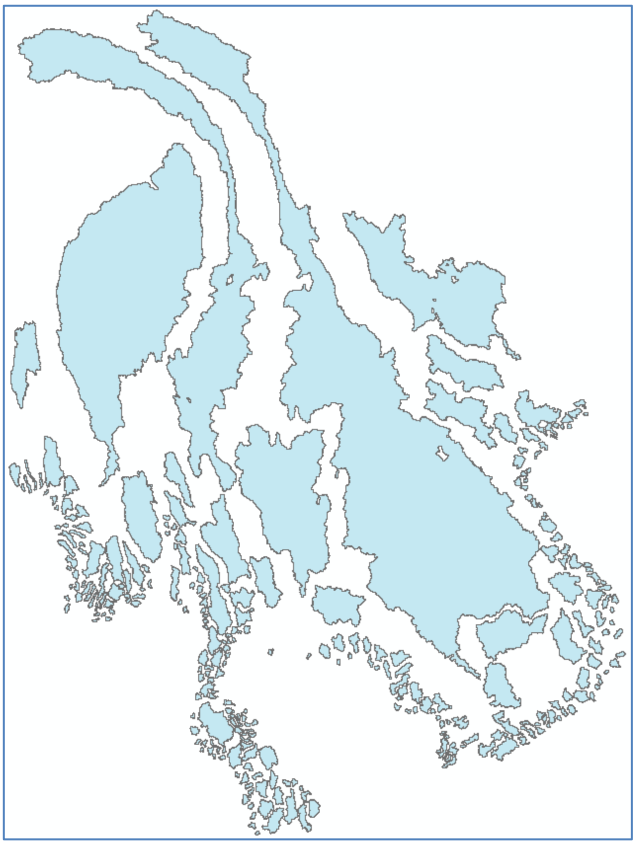


Fig. 2.3 River basins in the Indochina Peninsula region provided by the scale-free stream-flow network dataset

To run a hydrological model with study area covering many river basins, it is needed to join those individual topographic data into a large topographic map that suits the study area. Hence, required physiographic information for hydrological models such as catchment area, river length, elevation, slope, and flow direction will be processed and joined into a large topographic map.

The most important thing that needs to be considered to join individual river basin data into a large topographic map is how to process the data of overlapped grid cells at the boundary of those river basins. An example of joining flow direction data is showed in Fig. 2.4 and Fig. 2.5.

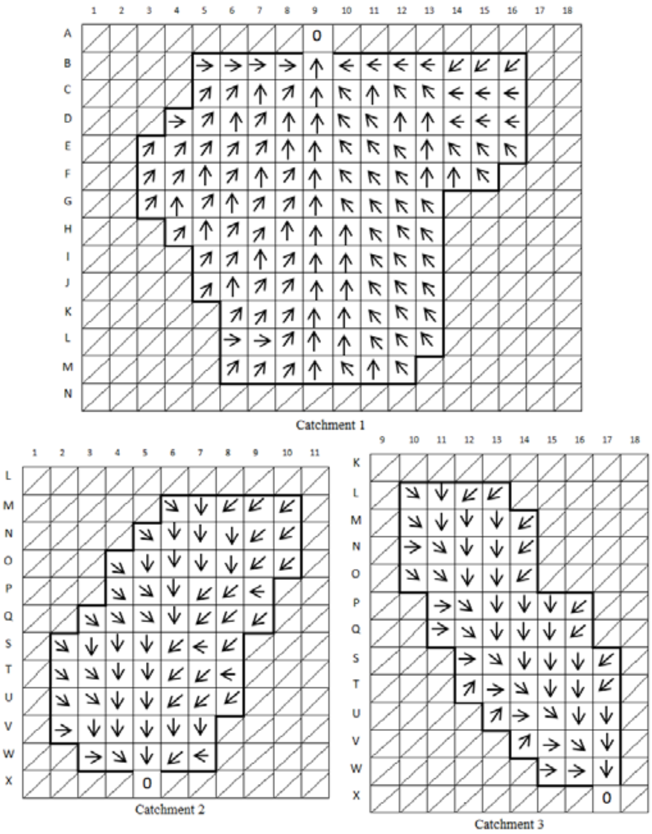


Fig. 2.4 Example of flow direction data before joining (Arrows indicate flow direction)

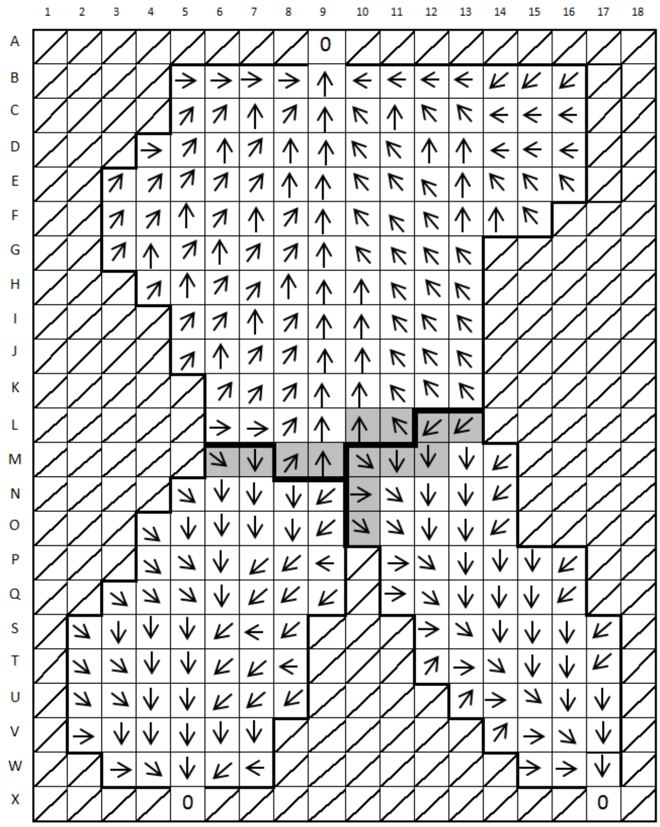


Fig. 2.5 Flow direction after joining (Shaded grid cells: overlapped grid cells; bold lines: basin divides)

The proposed method is to keep the topographic information of overlapped grid cells which have a larger area. Overlapped grid cells with smaller area will be removed but information about grid cell area will be added into the neighbour ones following its flow direction. This will keep catchments area unchanged when they are joined into a large topographic map. Flow direction of the grid cells which flow into removed grid cells will be changed to their neighbour ones in the same basin. Fig. 2.6 shows the 5-arc-minute spatial resolution flow accumulation map of the Indochina Peninsula region after joining all individual river basins in the area.

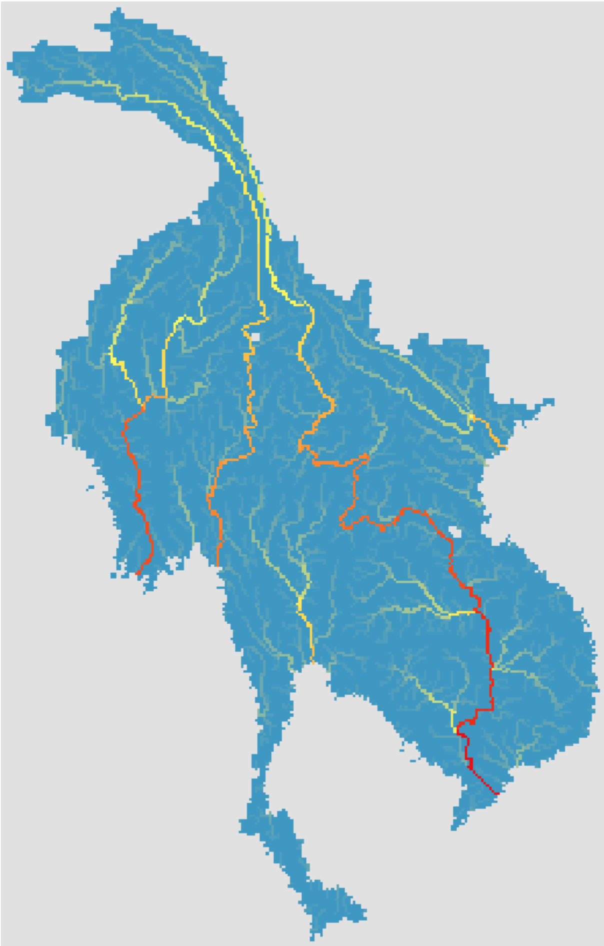


Fig. 2.6 Flow accumulation map of the Indochina Peninsula region

2.4 General circulation model data

General circulation models (GCMs) are widely used for projections of future climate change. The periodic assessment reports of climate change by IPCC have relied heavily on GCM simulations of future climate driven by various emission scenarios. In the Fifth Assessment Report of IPCC, data set of more than 20 GCMs is fully utilized (Hartmann et al., 2013). These GCM simulations were performed under the Coupled Model Intercomparison Project Phase 5 (CMIP5). CMIP5 is an internationally coordinated activity to perform climate model simulations for a common set of experiments from many major climate modelling centers in the world. The projections for the future climate change and the potential effects at regional and continental scales have been analyzed based on these archives.

There are several GCMs providing 3-hourly and daily runoff generation data. According to the data availability and spatial resolution, two GCMs cooperatively produced by the Japanese research community were used in this study. They are the atmospheric general circulation model of the Meteorological Research Institute (MRI-AGCM) and the Model for Interdisciplinary Research on Climate (MIROC).

2.4.1 Atmospheric general circulation model MRI-AGCM

MRI-AGCM is the global atmospheric general circulation model developed by Meteorological Research Institute (MRI) and Japan Meteorological Agency (JMA). This model is based on the JMA's operational weather prediction model with implementation of quasi-conservative semi-Lagrangian dynamics, a radiation scheme, and a land surface scheme developed for a climate model (Mizuta et al., 2006). Simulations of the present-day and future climates were performed by using the observed sea surface temperature (SST) and SST change projected by atmosphere-ocean coupled models as the lower boundary condition.

The latest version of the MRI atmospheric general circulation model is the MRI-AGCM3.2. The model simulations were run at spatial resolution of 20-km (MRI-AGCM3.2S) and 60-km (MRI-AGCM3.2H). The model is equipped with multiple cumulus convection schemes that can be easily switched. There are three cumulus convection schemes used for the multi-physics ensemble simulations including the prognostic Arakawa-Schubert cumulus convection scheme (Arakawa and Schubert, 1974), a new cumulus convection scheme named as “Yoshimura scheme” (Yukimoto et al., 2011), and the Kain-Fritsch convection scheme (Kain and Fritsch, 1993).

2.4.2 Model for Interdisciplinary Research on Climate

The Model for Interdisciplinary Research on Climate (MIROC) was jointly developed at the Center for Climate System Research (CCSR), University of Tokyo; National Institute for Environmental Studies (NIES); and Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The MIROC5 is the newest version of the model with the spatial resolution of about 140-km.

The cumulus scheme employed in MIROC5 was developed by Chikira and Sugiyama (Chikira, 2010; Chikira and Sugiyama, 2010). The parameterization schemes of cloud convection in MIROC5 have been significantly improved in comparison with previous version (Watanabe et al. 2010). The dynamical cores of the atmosphere model and the radiation, cumulus convection, turbulence, and aerosol schemes have all been upgraded in MIROC5. For the ocean and land surface models in MIROC5, the sea ice component was improved, and an advanced version of the river routing model Total Runoff Integrating Pathways (Oki and Sud 1998) has been incorporated.

References

Arakawa, A., and W. H. Schubert (1974) Interaction of a cumulus cloud ensemble with the large-scale environment, Part I, *J. Atmos. Sci., 31(3), pp. 674–701*.

Chikira, M. (2010) A cumulus parameterization with state-dependent entrainment rate. Part II: Impact on climatology in a general circulation model. *J. Atmos. Sci.*, 67, 2194–2211.

Chikira, M. and M. Sugiyama (2010) A cumulus parameterization with state-dependent entrainment rate. Part I: Description and sensitivity to temperature and humidity profiles. *J. Atmos. Sci.*, 67, 2171–2193.

Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai (2013) Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.*

Kain, J. S., and J. M. Fritsch (1993) Convective parameterization for meso-scale models: The Kain-Fritsch scheme, in The Representation of Cumulus Convection in Numerical Models, *Meteorol. Monogr., vol. 24,* edited by K. A. Emanuel and D. J. Raymond, pp. 165–170, Am. Meteorol. Soc., Boston.

Lehner, B., Verdin, K., Jarvis, A. (2006) HydroSHEDS Technical Documentation. *World Wildlife Fund US, Washington, DC.* Available at http://hydrosheds.cr.usgs.gov.

Masutani, K., Akai, K., Magome, J. (2006) A new scaling algorithm of gridded river networks, *Japan Society of Hydrology and Water Resources*, 19 (2), 139 – 150 (in Japanese).

Mizuta, R., K. Oouchi, H. Yoshimura, A. Noda, K. Katayama, S. Yukimoto, M. Hosaka, S. Kusunoki, H. Kawai, and M. Nakagawa (2006) 20-km-mesh global climate simulations using JMA-GSM model-mean climate states. *J. Meteor. Soc. Japan*, 84, 165–185.

Oki, T., and Y. C. Sud (1998) Design of Total Runoff Integrating Pathways (TRIP) – A Global River Channel Network. *Earth Interactions*, vol. 2.

Watanabe, M., T. Suzuki, R. Oishi, Y. Komuro, S. Watanabe, S. Emori, T. Takemura, M. Chikira, T.Ogura, M. Sekiguchi, K. Takata, D. Yamazaki, T. Yokohata, T. Nozawa, H. Hasumi, H. Tatebe, and M. Kimoto (2010) Improved climate simulation by MIROC5: Mean states, variability, and climate sensitivity, *J. Climate*, 23, 6312–6335.

Yukimoto, S., et al. (2011) Meteorological Research Institute-Earth System Model version 1 (MRI-ESM1), *Model description, Tech. Rep. 64, 88 pp., Meteorol. Res. Inst., Tsukuba, Japan*.

Chapter 3

River discharge projection in the Indochina Peninsula region under a changing climate using the MRI-AGCM3.2S dataset

3.1 Introduction

The Indochina Peninsula region, comprising Vietnam, Laos, Cambodia, Thailand, Myanmar and some parts of China, is known to be one of the most disaster prone areas in the world. This is a developing region with a large and growing population, abundant low-lying areas, reliance on agricultural sector, and dependence upon natural resources. Thus, the region is at risk and confronting significant challenges from impacts of climate change.

According to the observations of climate change considered by the Intergovernmental Panel on Climate Change (IPCC), the average surface temperature in the Indochina Peninsula region has increased about 0.6 to 1.0 degree Celsius over the last century. It is also projected to increase about 1.25 degree Celsius by the end of the 21st century. Changes in the water cycle in the region are also projected to occur in a warming climate. The Indochina Peninsula region is likely to experience greater amount of precipitation and an increase in runoff (Hartmann et al., 2013).

With the warming of surface temperature in the region, the frequency of occurrence of climate extremes in the region is expected to change. Frequencies and magnitudes of water-related disasters such as floods, droughts and water scarcity are predicted to increase due to changes in heavy rainfall events. To cope with water-related disasters induced by global warming mentioned above, projection of river discharge is necessary. In this regards, hydrological and flow routing models play important roles in transferring the climate model outputs into discharge.

3.2 Methods

In this chapter, river discharge in the Indochina Peninsula region was simulated using a distributed flow routing model (1K-FRM) with kinematic wave flow approximation. The input data for flow routing model 1K-FRM were provided by the latest 20 km spatial resolution general circulation model MRI-AGCM3.2S which has been developed by the Meteorological Research Institute, Japan Meteorology Agency (Kitoh et al., 2009). MRI-AGCM3.2S provides various atmospheric and hydrologic variables for three climate experiments:

- Present climate experiment: 1979-2008
- Near future climate experiment: 2015-2044
- Future climate experiment: 2075-2104

River discharge in the Indochina Peninsula region was projected by feeding 3-hourly runoff generation data, which were simulated by a land-surface process model (SiB model) embedded in MRI-AGCM3.2S, into 1K-FRM.

The model parameters of the flow routing model 1K-FRM are the width of the flow B and Manning roughness coefficient n. The value of B is determined using the regression relationship $B = a.S^c$, where S is the catchment area, and a = 1.06 and c = 0.68 are constant parameters. The value of n is determined to $0.03m^{-1/3}s$ when the flow accumulation is larger than 500 km^2 and $1.0m^{-1/3}s$ when smaller than 500 km^2. These values were chosen in reference to other applications by Tachikawa et al. (2011) and Hunukumbura et al. (2012).

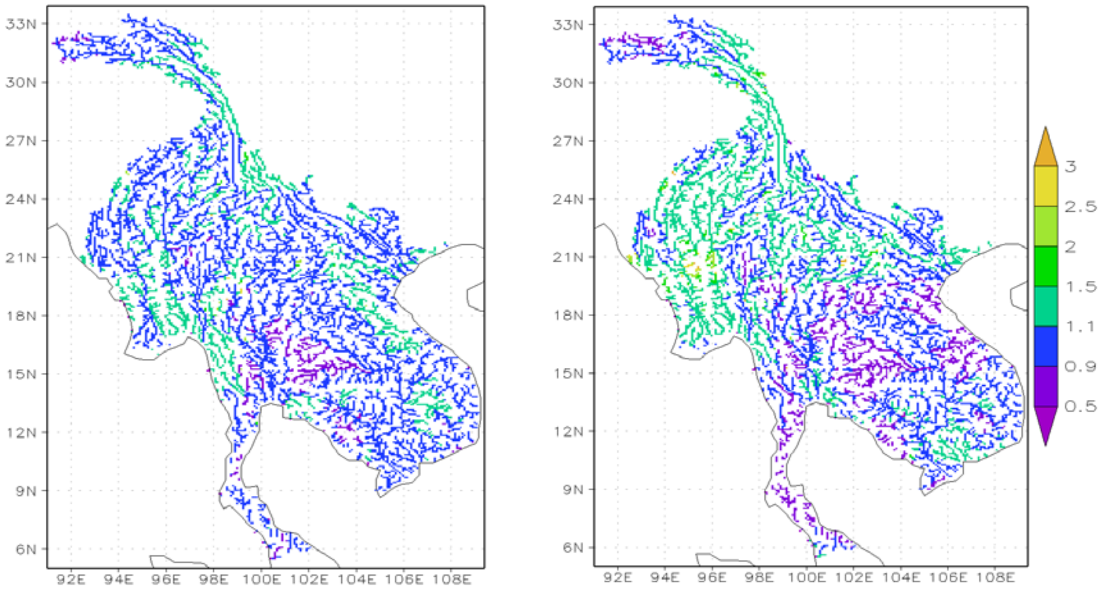
Simulated river discharge in the present climate experiment, the near future climate experiment and the future climate experiment were compared to examine the changes in river discharge in the region under climate change. Ratio of annual mean discharge, mean of annual maximum daily discharge, and mean of annual minimum daily discharge in the near future climate experiment and future climate experiment to the one in the present climate were calculated and analyzed.

3.3 Future changes in river discharge in the Indochina Peninsula region under a changing climate

3.3.1 Changes in water resources

Annual mean simulated river discharge for three climate experiments was calculated and used to analyze the changes in water resources in the Indochina Peninsula region.

Fig. 3.1 shows the change ratio of annual mean discharge for the near future climate and the future climate to the present climate experiment. From Fig. 3.1a, it can be seen that there are not so much changes in annual mean discharge in the near future. The increases in annual mean discharge with the ratio smaller than 1.5 can be detected at the most upper parts of Salween and Mekong River basin, the lower part of Irrawaddy River basin, and western part of Vietnam. Only eastern part of Chao Phraya River basin shows a trend of decreasing in annual mean river flow with the ratio is between 0.5 and 0.9.



(a) (b)

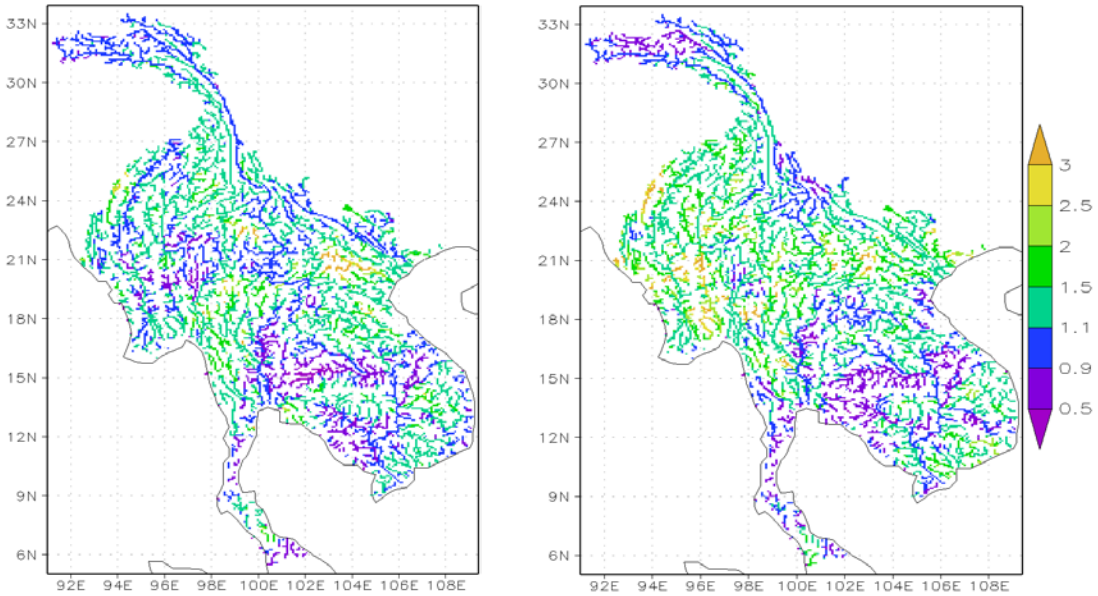
Fig. 3.1 Ratio of annual mean discharge in the near future climate (a) and in the future climate (b) to the one in the present climate

Fig. 3.1b shows a similar trend with higher intensity in the future climate experiment. We can see that the area with changes in annual mean discharge and ratio range become larger, especially at the middle and lower part of Irrawaddy River basin, and eastern part of Chao Phraya River basin. However, the annual mean flow in the future climate tended to decrease in the central part of Vietnam. The change ratio is lower than 0.9.

3.3.2 Changes in flood risk

Annual maximum daily discharge data for three climate experiments were compiled and were analyzed.

The change ratio of mean of annual maximum daily discharge for the near future climate and the future climate with respect to the present climate experiment are shown in Fig. 3.2.



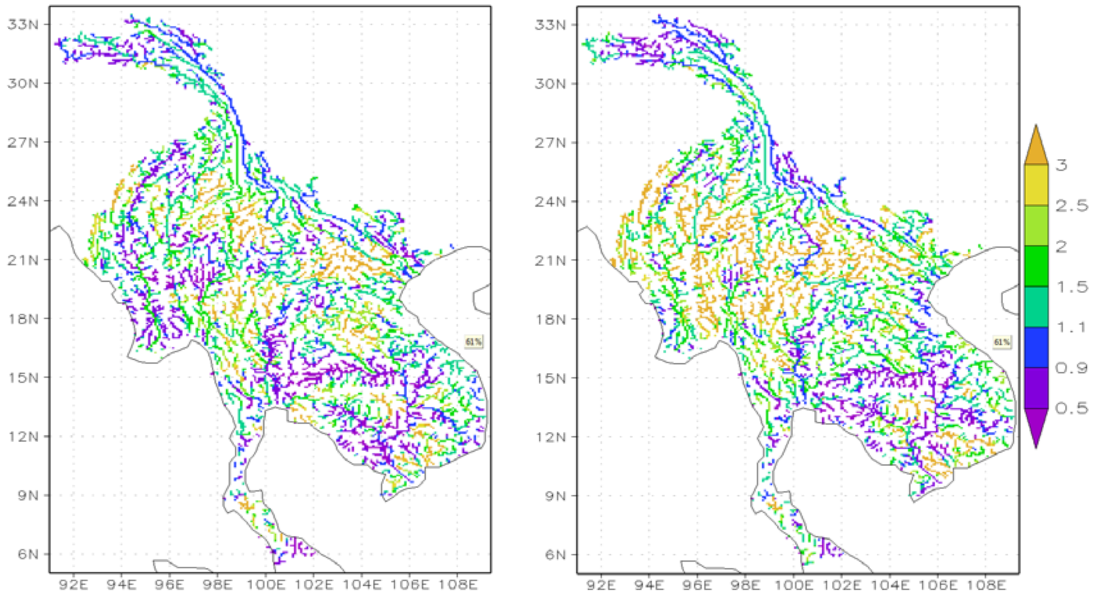
(a) (b)

Fig. 3.2 Ratio of mean of annual maximum daily discharge for the near future climate to the present climate (a), and the future climate to the present climate (b)

For the near future climate experiment, the mean of annual maximum daily discharge has significant changes at the upper and lower part of Salween River basin, north-western part of Vietnam, and eastern part of Chao Phraya River basin.

The changes, which were detected in the near future climate experiment, become more visible in the future climate experiment. Irrawaddy River basin and Red River basin showed a noticeable increasing of mean of annual maximum daily discharge in the future climate experiment. The ratio at some areas are larger than 2.5. It means that the risk of flooding at those areas will increase.

The ratio of the standard deviation of the annual maximum daily discharge for the near future climate and the future climate to the present climate experiment were also calculated and analysed. Fig. 3.3 shows the ratio of standard deviation of annual maximum daily discharge for the near future climate to the present climate experiment (Fig. 3.3a), and for the future climate to the present climate experiment (Fig. 3.3b).



(a) (b)

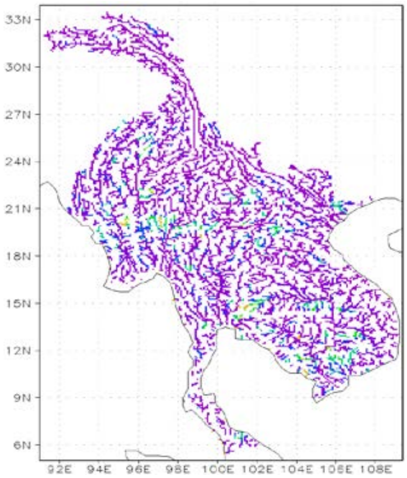
Fig. 3.3 Ratio of standard deviation of annual maximum daily discharge for the near future to the present climate (a), and the future to the present climate (b)

The standard deviation also showed a similar trend to the changes of mean of annual maximum daily discharge. The increases of standard deviation of annual maximum daily discharge can be found in Irrawaddy River basin, Salween River basin, and Red River basin.

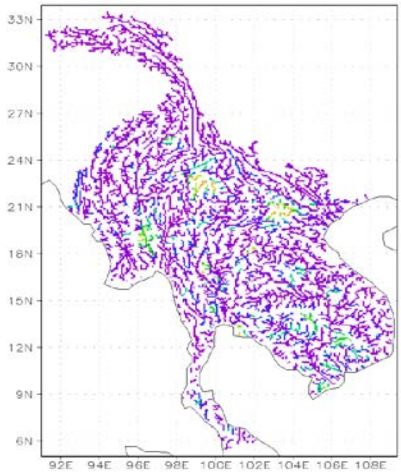
In addition, the Generalized Extreme Value (GEV) distribution was fitted to the annual maximum daily discharge for each climate experiment. The standard least-square criterion (SLSC) was used to evaluate the goodness-of-fit of the distribution (Takara et al., 1994). Then, the 10-year return period discharge for each climate experiment was obtained.

According to Takara and others, the critical value of SLSC is 0.04. And, with a sample size of hydrological data smaller than 30, SLSC < 0.07 is acceptable to river discharge frequency analysis (Hayashi et al., 2012).

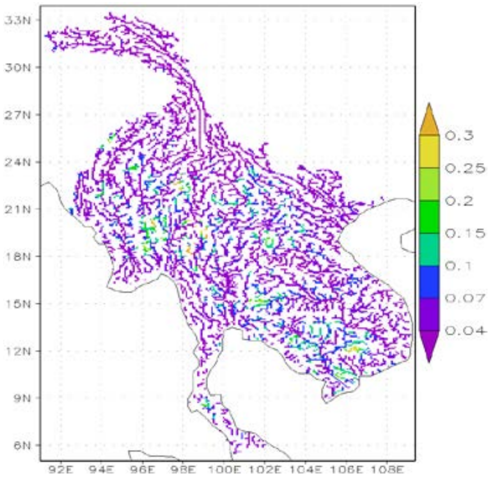
Fig. 3.4 shows the SLSC values for fitting the GEV distribution to the annual maximum daily discharge in the present, the near future and the future climate experiments. It can be seen that the SLSC values for each climate experiment in the Indochina Peninsula region are acceptable.



(a)



(b)



(c)

Fig. 3.4 SLSC values for fitting the GEV distribution to the annual maximum daily discharge for the present (a), the near future (b), and the future climate (c)

The change ratio of 10-year return period maximum daily discharge for the near future climate and the future climate with respect to the present climate are showed in Fig. 3.5. The spatial pattern of the change ratio of 10-year return period discharge showed a similarity to the change ratio of the mean of annual maximum daily discharge with significant changes in Irrawaddy River basin, Red River basin and lower part of Mekong River basin.

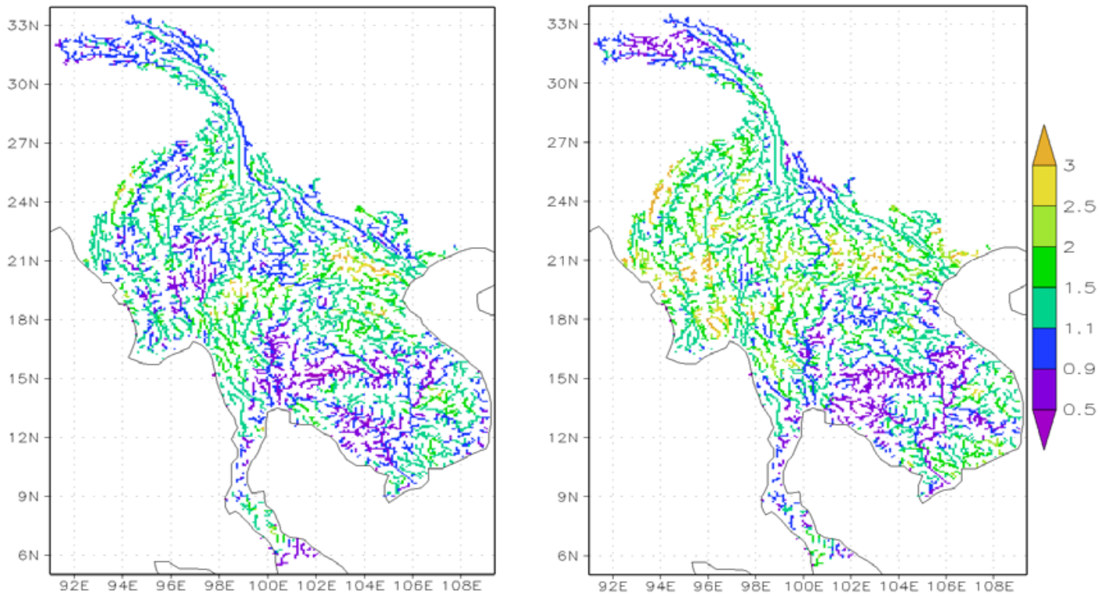


Fig. 3.5 Ratio of the 10-year return period annual maximum daily discharge for the near future climate (left) and the future climate (right) to the present climate

3.3.3 Changes in drought risk

The change in drought risk in the Indochina Peninsula region was also examined by comparing the mean of annual minimum daily discharge in the near future climate and the future climate experiment with those values in the present climate.

Fig. 3.6 shows the ratio of mean of annual minimum daily discharge in the near future climate and in the future climate experiments to the one in the present climate experiment.

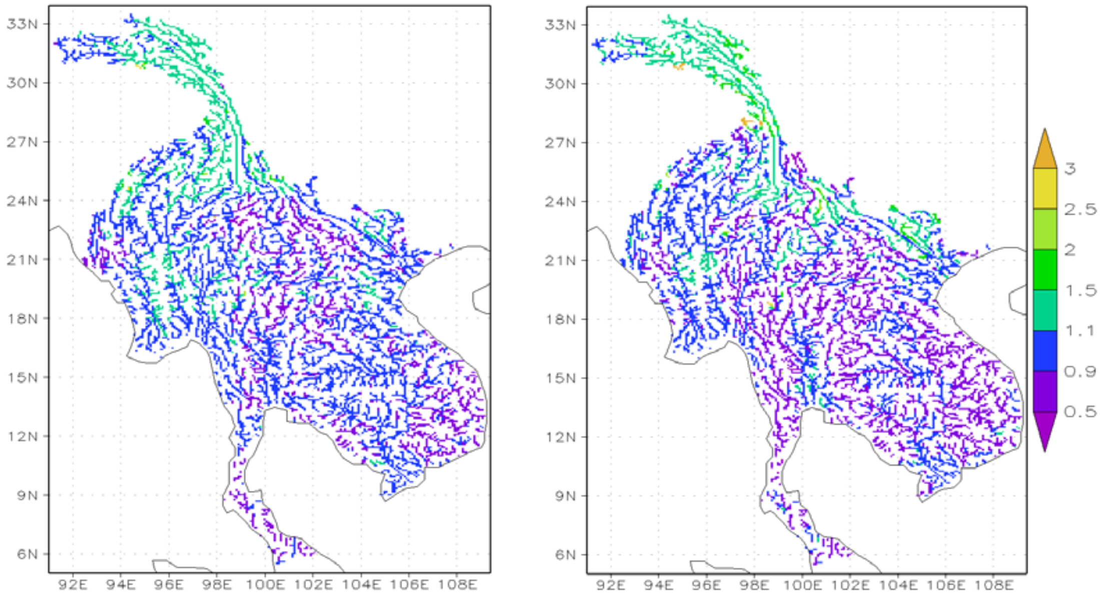


Fig. 3.6 Ratio of mean of annual minimum daily discharge for the near future climate to the present climate (a), and the future climate to the present climate (b)

From Fig. 3.6, it can be seen that there is a decrease trend at the middle part of Mekong River basin in the territory of Lao PDR, western part of Chao Phraya River basin, and the south-eastern part of Indochina Peninsula, especially the southern part of Vietnam. And this trend becomes clearer in the future climate experiment.

The SLSC values and change ratio of the 10-year return period discharge for annual minimum daily discharge in each climate experiment was also calculated using the Weibull distribution. The SLSC values for fitting Weibull distribution and change ratio of the 10-year return period discharge for the annual minimum discharge are showed in Fig. 3.7 and Fig. 3.8.

The SLSC values for fitting the Weibull distribution showed higher values than critical value in some locations with small catchment size (see Fig. 3.7). However, the values in most of large river basins were less than 0.07, the SLSC critical value.

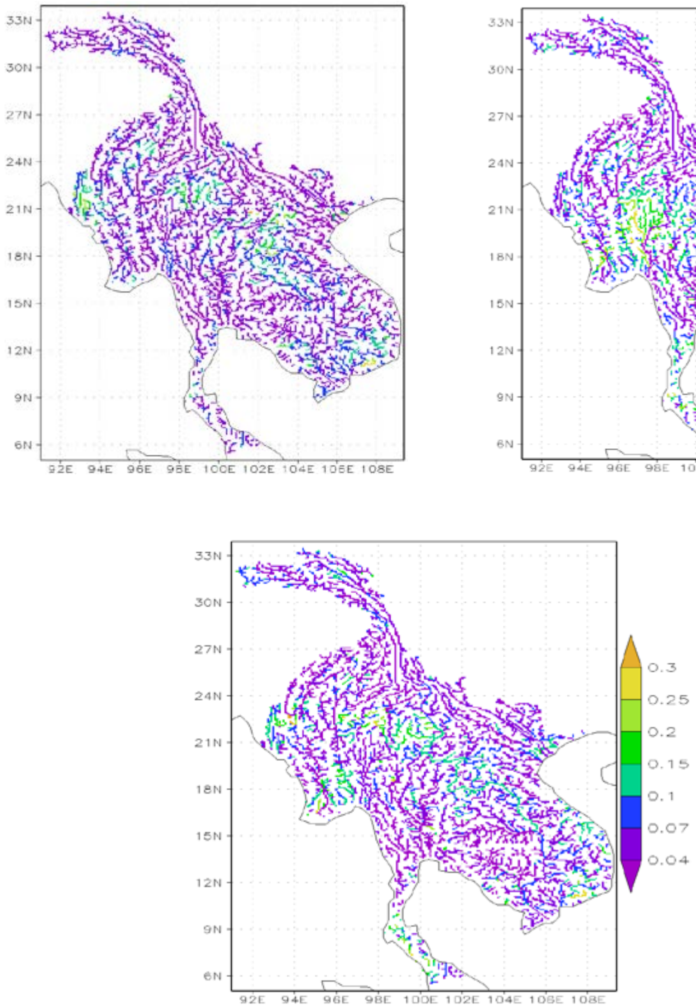


Fig. 3.7 SLSC values for fitting the Weibull distribution to the annual minimum daily discharge for the present (a), the near future (b), and the future climate (c)

Fig. 3.8 shows a similar pattern to the change ratio of mean of annual minimum daily discharge. For 10-year return period minimum discharge, the decrease of minimum discharge in the Chao Phraya River basin, and in the central and southern part of Vietnam became more visible.

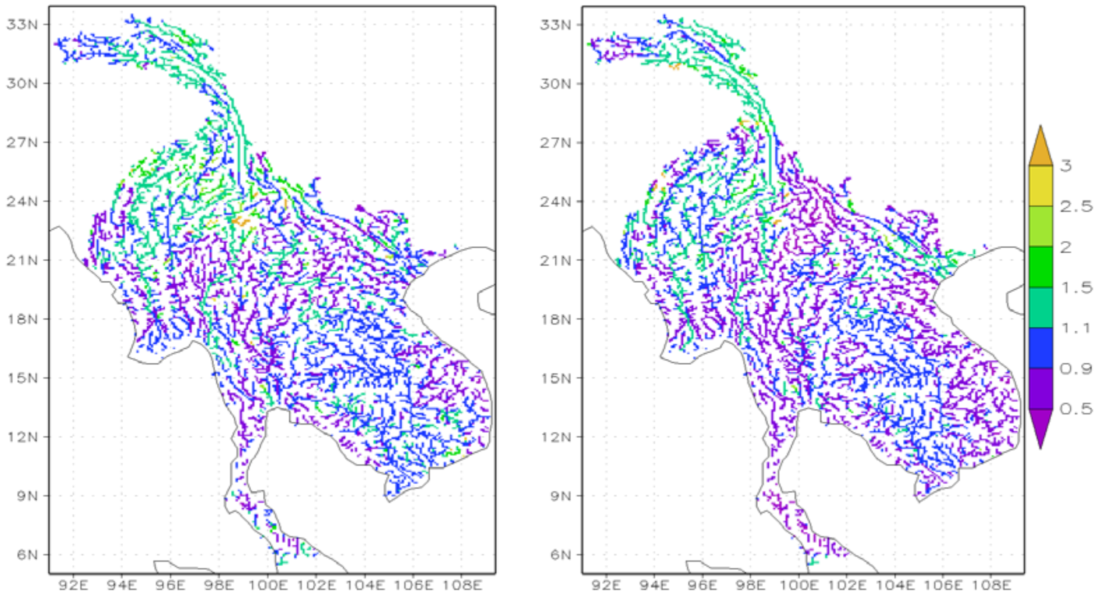


Fig.3.8 Ratio of the 10-year return period minimum daily discharge for the near future to the present climate (a), and the future to the present climate (b)

3.4. Conclusion

The impacts of climate change on river flow in the Indochina Peninsula region were analysed using distributed flow routing model 1K-FRM and runoff generation data which were generated by the latest 20km resolution general circulation model MRI-AGCM3.2S. River discharge was projected with the kinematic wave flow model with 5-minute spatial resolution DEM data for three climate experiments: the present climate (1979-2008), the near future climate (2015-2044), and the future climate (2075-2104).

In the Irrawaddy River basin (Myanmar), the annual mean discharge and mean of annual maximum daily discharge tended to increase in the near future climate experiment. The increases were much clearer in the future climate experiment. A same trend can be detected at Red River basin (Vietnam). Hence, flood risk is expected to increase in those river catchments. They would be hotspot basins on flood risk under climate change.

Drought risk was also found in the middle part of Mekong River basin and in the central and southern part of Vietnam. The mean of annual minimum daily discharge at locations mentioned above showed a decrease in the near future climate experiment. And the areas with decreasing in discharge were expanded in the future climate experiment.

In conclusion, a clear change of river flow in the Indochina Peninsula region was detected with the degree of change differs from location to location. It became clearer in the future climate experiment. The increase of flood risk was found in the Irrawaddy River basin (Myanmar) and Red River basin (Vietnam). The risk of droughts tended to increase in the middle part of Mekong River basin (Lao PDR) and in the central and southern part of Vietnam.

For further works, statistical analysis will be applied to confirm the changes in river discharge which were detected in the Indochina Peninsula region. A more detailed distributed hydrological model with dam operation function should be developed for hotspot river basins in the region with significant changes in river discharge.

References

Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai (2013) Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.*

Hayashi, H., Tachikawa, Y., Shiiba, M., Yorozu, K., Kim, S. (2012) Introducing a statistical hypothesis testing into SLSC goodness-of-fit evaluation for hydrological frequency analysis models, *Journal of Japan Society of Civil Engineers, B1 (Hydraulic Engineering)*, 68(4), I1381–I1386 (in Japanese).

Hunukumbura, P. B. & Tachikawa, Y. (2012) River discharge projection under climate change in the Chao Phraya river basin, Thailand, using the MRI-GCM3.1S dataset. *Journal of the Meteorological Society of Japan* 90A, 137 – 150.

Kitoh, A., T. Ose, K. Kurihara, S. Kusunoki, M. Sugi, and KAKUSHIN Team-3 Modeling Group (2009) Projection of changes in future weather extremes using super-high-resolution global and regional atmospheric models in the KAKUSHIN Program: Results of preliminary experiments. *Hydrological*

Research Letters, 3, 49–53.

Masutani, K., Akai, K., Magome, J. (2006) A new scaling algorithm of gridded river networks, *Japan Society of Hydrology and Water Resources*, 19 (2), 139 – 150 (in Japanese).

Tachikawa, Y., Takino, S., Fujioka, Y., Yorozu, K., Kim, S., Shiiba, M. (2011) Projection of river discharge of Japanese river basins under a climate change scenario, *Journal of Japan Society of Civil Engineers, B1 (Hydraulic Engineering)*, 67(1), 1–15 (in Japanese).

Takara, K., Stedinger, J. R. (1994) Recent Japanese contribution to frequency analysis and quantile lower bound estimator, Stochastic and Statistical Methods in Hydrology and Environmental Engineering, Hipel K.W. (ed.), *Kluwer Academic Publishers*, 1, 217-234.

Chapter 4

Statistical analysis of river discharge projected using the MRI-AGCM3.2S dataset in the Indochina Peninsula region

4.1 Introduction

To evaluate the impacts of climate change on hydrology and water resources, one effective approach is to use outputs of general circulation models (GCMs) as inputs for hydrological models. Many GCMs have been developed to simulate the present climate and have been used to project future climate change. They serve as a powerful tool for studying global climate and its variability. The climate simulations from the GCMs can be converted by hydrological models to relevant water resources variables for evaluating the hydrologic cycle and water resources effects of climate change.

In the previous chapter, chapter 3, river discharge in the Indochina Peninsula region was simulated using a super-high-resolution atmospheric general circulation model MRI-AGCM3.2S (Kitoh et al., 2009) with 20 km spatial resolution and a distributed flow routing model with kinematic wave approximation. The MRI-AGCM3.S runoff generation data for the present climate experiment (1979-2008), the near future climate experiment (2015-2044), and the future climate experiment (2075-2104) were used as input data for the flow routing model. And the relative change in river discharge between the future climate experiment and the present climate experiment were analysed to examine the potential changes in river discharge under climate change (Duong et al., 2013).

In order to investigate whether the changes in river discharge in the Indochina Peninsula region are statistically significant or just occur by chance, the statistical significance test was performed. The statistical significance of river discharge changes was also analysed to locate possible hotspot basins in the region where significant changes related to floods, droughts, and water resources could occur.

4.2 Methods

The statistical significance of river discharge changes in the Indochina Peninsula region was assessed with a comparison of means of projected river discharge data for the near future climate experiment and the future climate experiment with those for the present climate experiment. It is to evaluate whether the changes in river discharge are statistically significant or just occur by chance.

The approach for comparing those statistics is chosen based on the distribution of projected river discharge data. If the data sample is normally distributed, a parametric approach can be employed to determine whether the difference between means of projected river discharge is statistically significant or not. In cases where the data samples follow non-normal distribution, non-parametric approach is used.

4.2.1 Test for normality

In this study, Shapiro-Wilk W test (Gilbert, 1987) was applied for data normality test. The W test is performed by testing the following null hypothesis H_0: the sample data are normally distributed. The results of the test for normality are shown in the section of Test for normality. Based on those results, statistical significance testing methods were chosen.

For sample size of n, the W test statistic is calculated as follows:

$$W = \frac{1}{d}\left[\sum_{i=1}^{k} a_i\left(x_{[n-i+1]} - x_{[i]}\right)\right]^2$$

where

$d = \sum_{i=1}^{n}(x_i - \overline{x})^2$;

k is n/2 for even n and (n-1)/2 for odd n;

coefficient a_i are functions of n and can be found in the statistical tables.

The null hypothesis H_0 will be rejected at the α significance level if W is smaller than the critical value W_α.

4.2.2 Test for statistically significant differences between two means

The parametric Welch correction t-test (Zar, 2010) was applied for the river discharge data which have a normal distribution. The non-parametric Mann-Whitney U test (Gilbert, 1987) was performed to test for statistical significance of non-normal distribution river discharge data.

The null hypothesis H_0 for the statistical significance testing can be defined as follows: there is no significant difference between annual mean discharge/mean of annual maximum daily discharge/mean of annual minimum daily discharge for the near future climate/the future climate and the present climate ($\mu_{\text{near future}} = \mu_{\text{present}}$, $\mu_{\text{future}} = \mu_{\text{present}}$).

Welch correction t-test

The t-test statistic is calculated by

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

where

$\bar{X}_1, \bar{X}_2$ are sample means;

s_1, s_2 are standard deviations;

n_1, n_2 are sample sizes.

In Welch correction t-test, the null hypothesis H_0 will be rejected if t-test statistic is larger than the critical value at α significance level, t_α.

Mann-Whitney U test

The procedure to calculate U test statistic as follows:

- Rank the combined set of data from two groups from smallest to largest.
- For each data in group 2, count the number of data in group 1 that have a smaller rank. The sum of these counts is U_1.
- For each data in group 1, count the number of data in group 2 that have a smaller rank. The sum of these counts is U_2.

- U test statistic = min (U_1, U_2)

In Mann-Whitney U test, the null hypothesis H_0 will be rejected if U test statistic is smaller than the critical value at α significance level, U_α.

4.3 Results and discussions

4.3.1 Test for normality

The results of data normality test using Shapiro-Wilk W test are shown in Fig. 4.1, Fig. 4.2 and Fig. 4.3. Those figures show the W statistic values of annual mean discharge, mean of annual maximum daily discharge, and mean of annual minimum daily discharge data for the present climate, the near future climate, and the future climate.

In the Shapiro-Wilk W test, if the calculated W statistic is smaller than the critical W statistic value, the null hypothesis is rejected. The critical W statistic value can be obtained from table of W critical values based on data sample size n and significant level α. In climate science, the significant level of 0.05 or 5% is often selected. With a data sample size of 30, the statistic table provides critical value $W^{cr}_{\alpha=0.05}$ = 0.927. Therefore, the sample data are not normally distributed when calculated W statistics are less than 0.927 (see Fig. 4.1, Fig. 4.2, and Fig. 4.3).

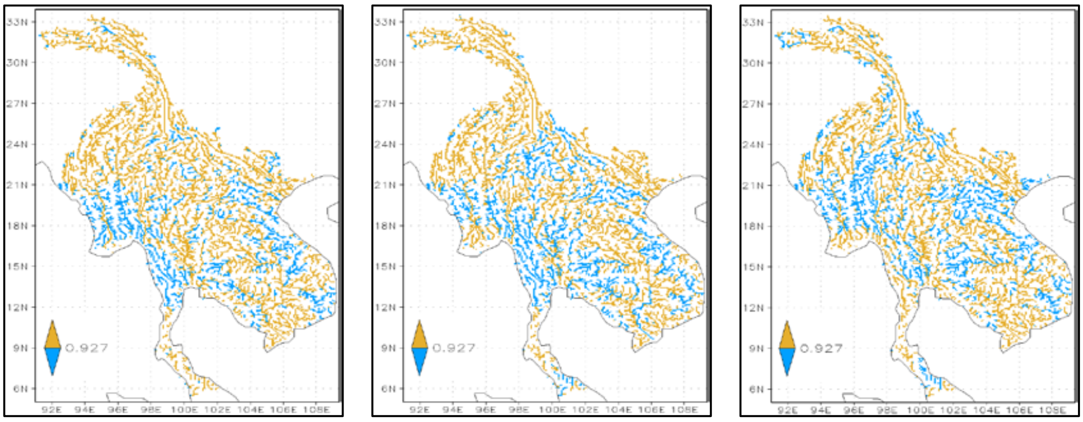


Fig. 4.1 W test statistic of annual mean discharge data for the present climate (left), the near future climate (middle), and the future climate (right)

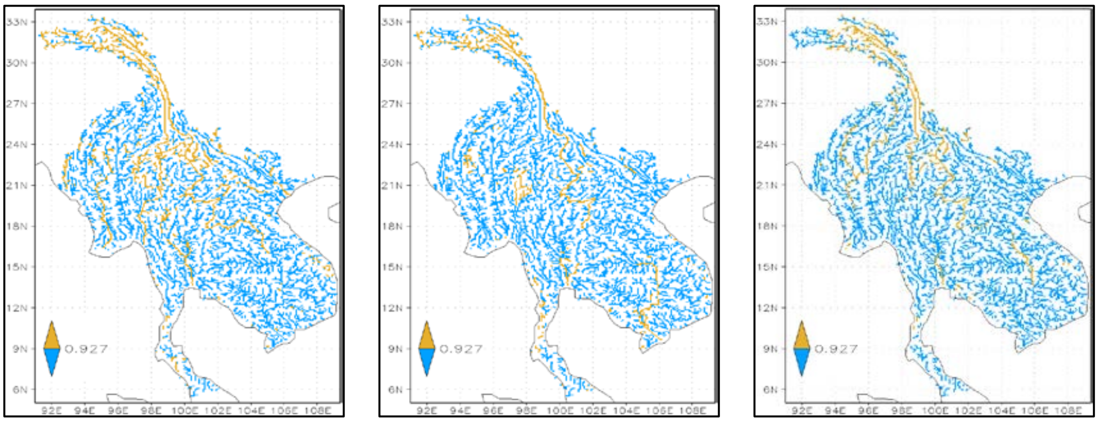


Fig. 4.2 W test statistic of mean of annual maximum daily discharge data for the present climate (left), the near future climate (middle), and the future climate (right)

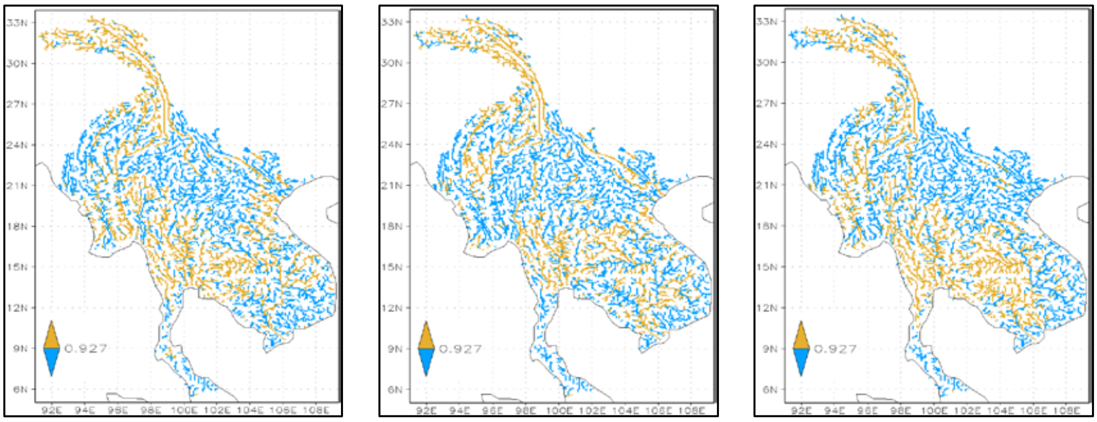


Fig. 4.3 W test statistic of mean of annual minimum daily discharge data for the present climate (left), the near future climate (middle), and the future climate (right)

4.3.2 Test for statistically significant differences between two means

Based on the results of data normality test, the test for statistical significance was carried out. If both river discharge data being compared are normally distributed, the parametric Welch correction t-test is used. In other cases, the non-parametric Mann-Whitney U test is applied.

Statistical significance of changes in annual mean discharge

The relative changes in annual mean discharge in the near future climate experiment and in the future climate experiment, and results of statistical significant test are shown in Fig. 4.4 and Fig. 4.5.

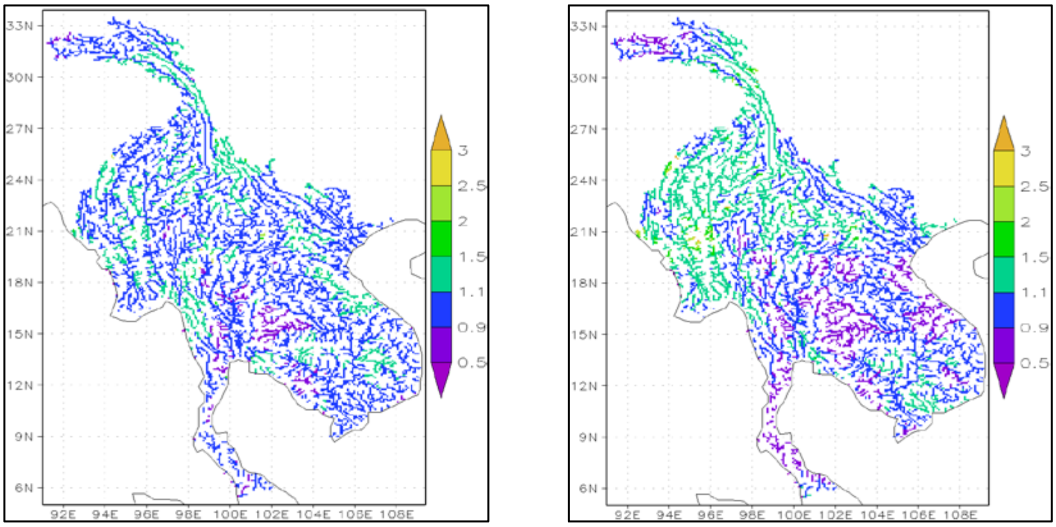


Fig. 4.4 Ratio of annual mean discharge for the near future climate to the present climate (left), and the future climate to the present climate (right)

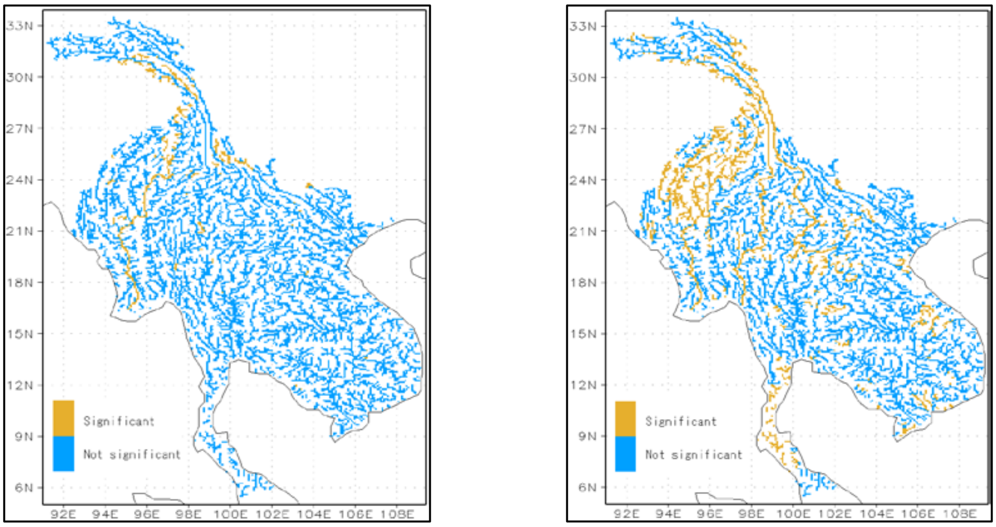


Fig. 4.5 Statistical significant differences between annual mean discharge for the near future climate and the present climate (left); and for the future climate and the present climate (right)

From Fig. 4.5, it can be seen that, in the near future climate, the change in annual mean discharge in the Indochina Peninsula region is statistically significant only in the main channel of the Irrawaddy River basin. In the future climate, annual mean discharge increases in all the Irrawaddy River basin and upper part of the Salween and Mekong River basin. The decrease in annual mean discharge was also detected at Chi-Mun sub-basin of the Mekong and in the central part of Vietnam. However, the changes in annual mean discharge are statistically significant only in middle and upper part of the Irrawaddy River basin, the main channel of the Salween River basin and upper part of the Mekong River basin's main channel.

Statistical significance of changes in mean of annual maximum daily discharge

Fig. 4.6 and Fig. 4.7 illustrate the relative change in mean of annual maximum daily discharge and results of statistical significant test.

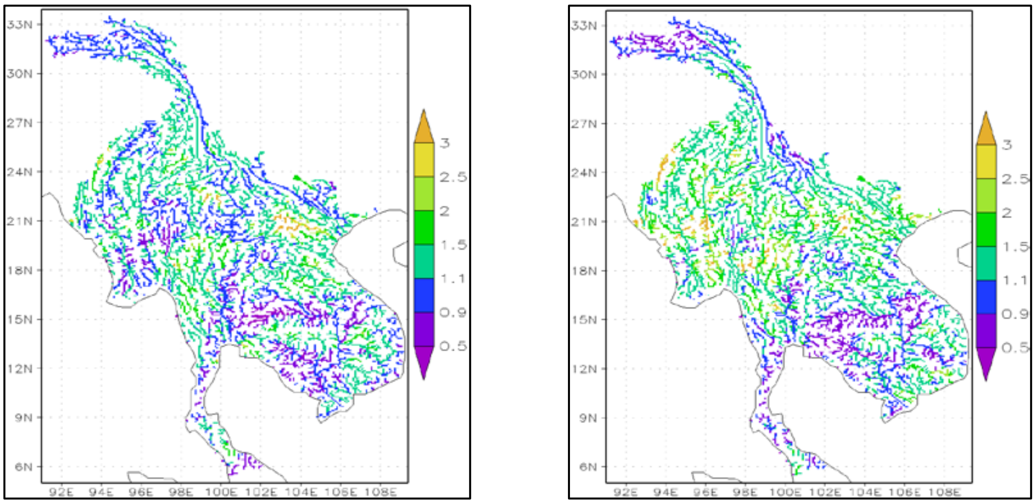


Fig. 4.6 Ratio of mean of annual maximum daily discharge for the near future to the present climate (left), and the future to the present climate (right)

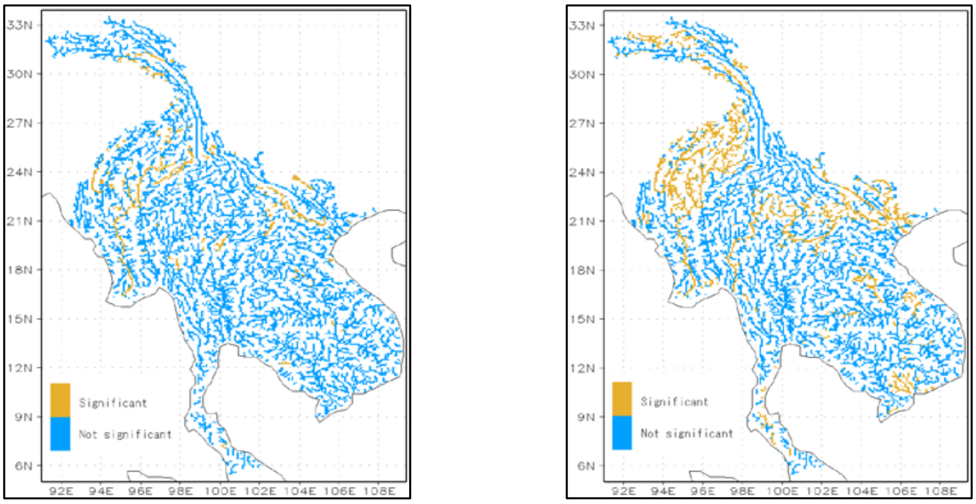


Fig. 4.7 Statistical significant differences between mean of annual maximum daily discharge for the near future and the present climate (left); and for the future and the present climate (right)

For the mean of annual maximum daily discharge, a majority part of the study area shows an increasing trend in the near future climate and in the future climate. The changes in mean of annual maximum daily discharge are statistically significant in the main channel of the Irrawaddy and the Red River basin in the near future climate (see Fig. 4.7). The statistical significance of river discharge change was found in the future climate at the Irrawaddy River basin, lower part of the Salween River basin's main channel, main channel of the Mekong River basin in the territory of Lao PDR, and the Red River basin.

Statistical significance of changes in mean of annual maximum daily discharge

The relative change in mean of annual minimum daily discharge in the near future climate experiment and in the future climate experiment, and results of statistical significant test are shown in Fig. 4.8 and Fig. 4.9.

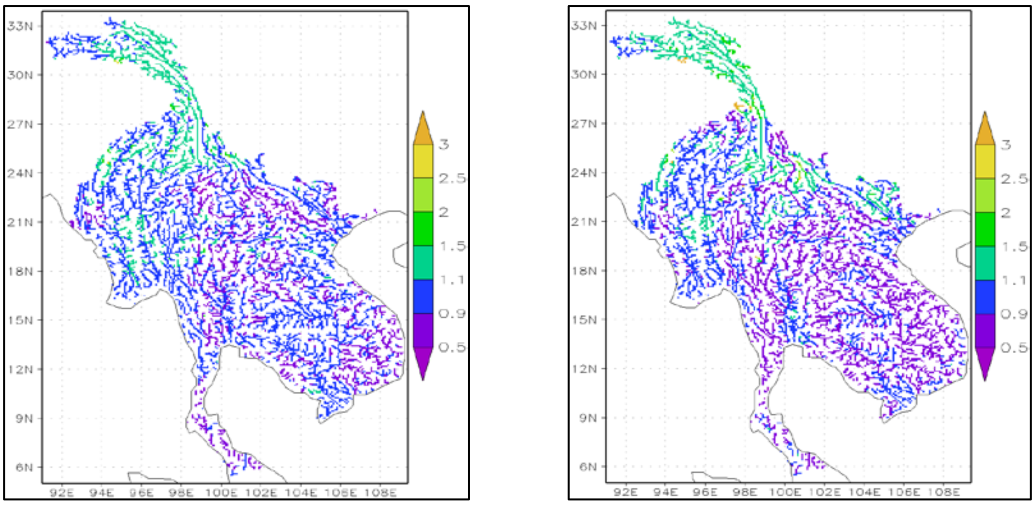


Fig. 4.8 Ratio of mean of annual minimum daily discharge for the near future climate to the present climate (left), and the future climate to the present climate (right)

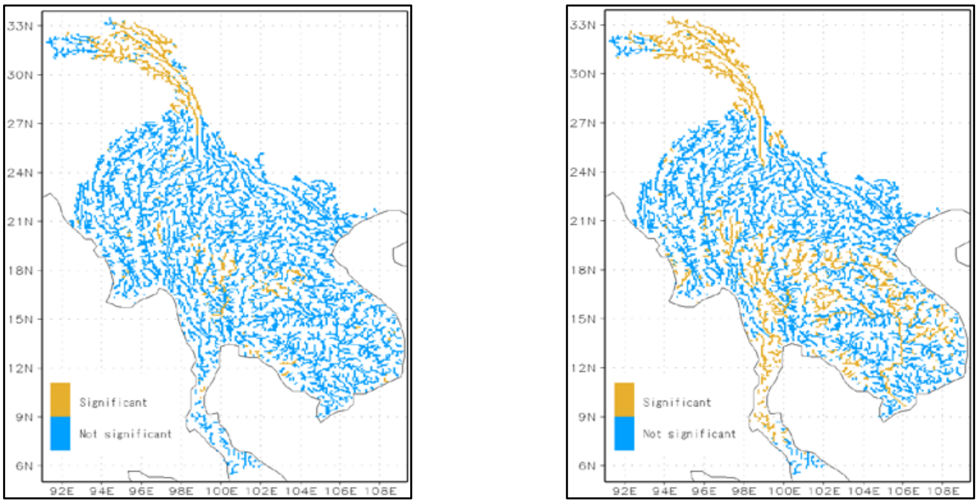


Fig. 4.9 Statistical significant differences between mean of annual minimum daily discharge for the near future and the present climate (left); and the future and the present climate (right)

In the near future climate, although the mean of annual minimum daily discharge shows an increase at the upper most part of the Salween River basin and the Mekong River basin, and decrease at the middle part of the Mekong and southern part of Vietnam; the change was detected statistically significant only at the upper most part of the Salween and the Mekong River basin (see Fig. 4.9).

The increase in mean of annual minimum daily discharge is more visible in the future climate. It is also found statistically significant. The decrease in mean of annual minimum daily discharge is statistically significant at the left tributary of the Chao Phraya River basin, the Chi-Mun sub-basin of the Mekong, and in the central part of Vietnam.

4.4 Conclusions

This study investigated the change in river flow under a changing climate in the Indochina Peninsula region using the distributed flow routing model 1K-FRM and MRI-AGCM3.2S dataset. Statistical analysis was carried out to examine the statistical significance of river discharge changes in the region.

A clear change in annual mean discharge and mean of annual maximum discharge was detected and found statistically significant at the Irrawaddy River basin in both near future climate and future climate. The increase in mean of annual maximum daily discharge is also statistically significant at the Red River basin. The statistical significance of change in mean of annual minimum daily discharge was confirmed at the upper most parts of the Salween and the Mekong River basin, and in the central part of Vietnam.

For future further work, the same procedure should be carried out using runoff generation data from different ensemble experiments or different GCMs to evaluate the uncertainty in climate projection.

References

Duong, D. T., Tachikawa, Y., Shiiba, M., Yorozu, K. (2013) River discharge projection in Indochina Peninsula under a changing climate using the MRI-AGCM3.2S dataset. *Journal of Japan Society of Civil Engineers*, Ser. B1 (Hydraulic Engineering), Vol. 69, No. 4, I_37-I_42.

Gilbert, R. O. (1987) *Statistical Methods for Environmental Pollution Monitoring*. Van Nostrand Reinhold Co., New York, 320 pp.

Kitoh, A., T. Ose, K. Kurihara, S. Kusunoki, M. Sugi, and KAKUSHIN Team-3 Modeling Group (2009) Projection of changes in future weather extremes using super-high-resolution global and regional atmospheric models in the KAKUSHIN Program: Results of preliminary experiments. *Hydrological Research Letters*, 3, 49–53, doi:10.3178/hrl.3.49.

Zar, J. H. (2010) Biostatistical Analysis. 5th Edition. *Pearson Prentice-Hall, Upper Saddle River, NJ*. 944 pp.

Chapter 5

Future changes and uncertainties in river discharge projected using different ensemble experiments of the MRI-AGCM and MIROC5 datasets

5.1 Introduction

In the Assessment Reports, the Intergovernmental Panel on Climate Change (IPCC) stated that the anthropogenic increasing of greenhouse gas concentrations is the main cause of the current global warming trend. According to the latest report on climate change published by the IPCC in 2013 (Hartmann et al., 2013), the global average surface temperature was reported to increase about 0.89 degree Celsius since 1901. Increases in surface temperature are likely to have many impacts on the hydrological cycle and associated extremes such as floods and droughts. As a consequence, researches on climate change and its impacts on hydrology and water resources have intensified in recent years.

Currently, general circulation models (GCMs) are the most effective tools for simulating present climate and projecting future climate. These models represent major Earth system components (atmosphere, oceans, land surface, sea ice) and their interactions. They are fundamental tools for climate change impact studies. However, despite major changes and improvements in climate modelling in recent years, many uncertainties in GCMs still remain. There are three main sources of uncertainty in GCM projections (Hawkins and Sutton, 2009; Knutti and Sedlacek, 2013):

- Natural climate variability: originating from natural process within the climate system
- Future emissions of greenhouse gases: arising from the limitations in our understanding of how future greenhouse gas emissions will change
- Modelling uncertainty: resulting from our ability to model the climate system

In addition, in climate change impact studies, uncertainty from GCM projections was found larger than from downscaling techniques or hydrological modelling (Kay et al., 2009; Gosling et al., 2011; Teng et al., 2012; Dobler et al., 2012). To address and reduce uncertainties arising from modelling experiments, several approaches were developed. Multi-model ensemble and multi-physics ensemble are two main approaches which have been used most frequently (Gualdi et al., 2011). Multi-model ensemble consists of simulations contributed by different climate models. And multi-physics ensemble combines different physical parameterizations in a single climate model.

In this chapter, river discharge in the Indochina Peninsula region was projected using different ensemble experiments from three different GCM datasets: the MRI-AGCM3.2S, the MRI-AGCM3.2H (Kitoh et al., 2009) and the MIROC5 (Watanabe et al., 2010). Outputs of these GCMs were obtained from the Innovative Program of Climate Change Projection for the 21st Century (the KAKUSHIN program) and the multi-model dataset archive of the Coupled Model Intercomparison Project Phase 5 (CMIP5). The analysis of future changes in river discharge in the region was carried out to address the differences in projections from a combination of ensemble experiments and to discuss their uncertainties.

5.2 Data and methods

River discharge in the Indochina Peninsula region was projected using flow routing model 1K-FRM. Runoff generation data from the MRI-AGCM3.2S (the 20-km model), the MRI-AGMC3.2H (the 60-km model), and the MIROC5 (the 150-km model) were used as input for flow routing model 1K-FRM for two 25-year periods:

- The present climate experiment: 1979-2003
- The future climate experiment: 2075-2099

Outputs from 10 ensemble simulations with 3 different cumulus convection schemes and 4 different sea surface temperature (SST) change patterns were used for river discharge projection (see Table 5.1).

Table 5.1 Summary of ensemble experiments for river discharge projection

<table>
<tr><th>Dataset</th><th>Spatial resolution</th><th>Cumulus convection scheme</th><th colspan="2">Sea surface temperature</th><th>Run name</th></tr>
<tr><td rowspan="2">MRI-AGCM3.2S</td><td rowspan="2">20 km</td><td rowspan="2">Yoshimura</td><td>Present</td><td>Observation</td><td>YS_20</td></tr>
<tr><td>Future</td><td>CMIP MME</td><td>YS_20_CMIP</td></tr>
<tr><td rowspan="7">MRI-AGCM3.2H</td><td rowspan="7">60 km</td><td rowspan="2">Yoshimura</td><td>Present</td><td>Observation</td><td>YS_60</td></tr>
<tr><td>Future</td><td>CMIP MME</td><td>YS_60_CMIP</td></tr>
<tr><td rowspan="5">Kain-Fritsch</td><td>Present</td><td>Observation</td><td>KF</td></tr>
<tr><td rowspan="4">Future</td><td>CMIP MME</td><td>KF_CMIP</td></tr>
<tr><td>Cluster 1</td><td>KF_cluster1</td></tr>
<tr><td>Cluster 2</td><td>KF_cluster2</td></tr>
<tr><td>Cluster 3</td><td>KF_cluster3</td></tr>
<tr><td rowspan="2">MIROC5</td><td rowspan="2">150 km</td><td rowspan="2">Chikira</td><td>Present</td><td>Observation</td><td>MIROC5_P</td></tr>
<tr><td>Future</td><td></td><td>MIROC5_F</td></tr>
</table>

For present climate experiments, the lower boundary conditions of ensemble simulations with different cumulus convection schemes were prescribed as observed monthly mean SSTs and sea ice concentrations during 1979-2003 according to the Hadley Centre Global Sea Ice and Sea Surface Temperature dataset (HadISST1; Rayner et al., 2003).

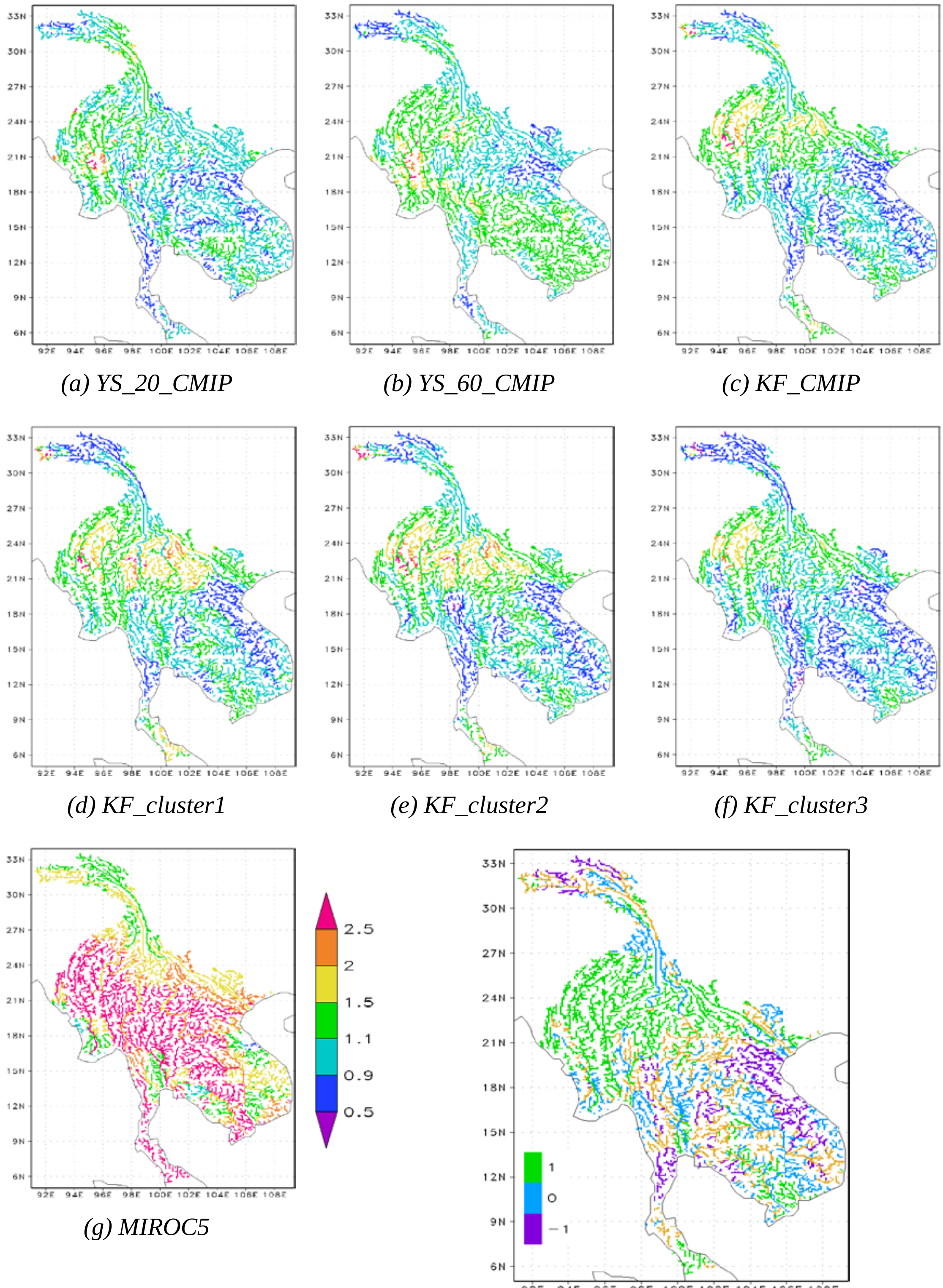
For future climate experiments, the future SST change was evaluated based on the Special Report on Emissions Scenarios A1B scenario (MRI-AGCM3.2S, MRI-AGCM3.2H) and the Representative Concentration Pathway 6 (RCP6) scenario (MIROC5). The SRES A1B scenario and the RCP6 scenario are more or less equivalent in term of CO_2 concentration. Four different future SSTs patterns were used for future climate projections. The first one is the multi-model ensemble mean of future SSTs from 18 CMIP3 models (CMIP MME). Other patterns were prepared using cluster analysis (cluster1, cluster2, cluster3). In cluster analysis, normalized tropical SST anomalies derived from 18 CMIP3 models were grouped to avoid subjective selection of a single model (Mizuta et al., 2008; Murakami et al., 2012a, Endo et al., 2012).

The ratio of projected river discharge in the future climate to the one in the present climate was calculated and analysed to examine the changes in river discharge in the Indochina Peninsula region under climate change. The statistical significance of river discharge change in the region was also assessed using the same procedures as presented in the previous chapters.

5.3. Results and discussions

5.3.1 Changes in annual mean discharge

The relative change and statistical significance differences between annual mean discharge in the future climate and in the present climate are illustrated in Fig. 5.1 and Fig. 5.2.

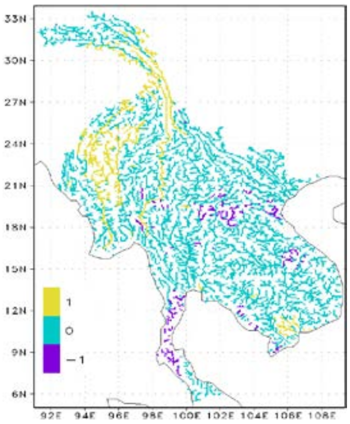


(a) YS_20_CMIP *(b) YS_60_CMIP* *(c) KF_CMIP*

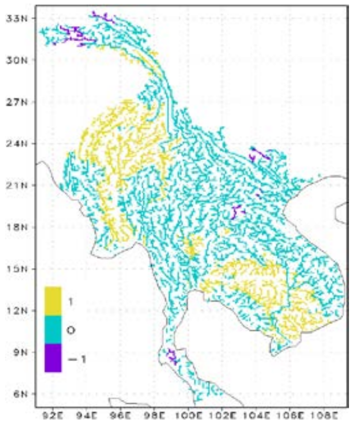
(d) KF_cluster1 *(e) KF_cluster2* *(f) KF_cluster3*

(g) MIROC5 *(h) Combination of 6 simulations*

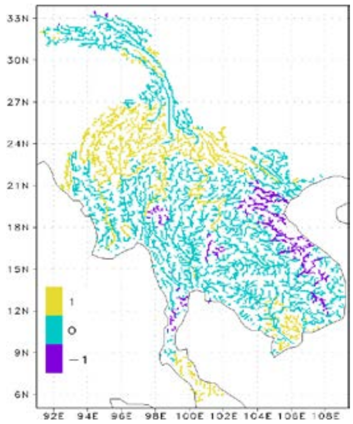
Fig. 5.1 Ratio of annual mean discharge in the future climate experiment to the one in the present climate experiment



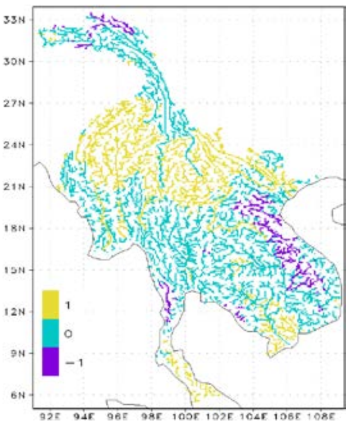
(a) YS_20_CMIP



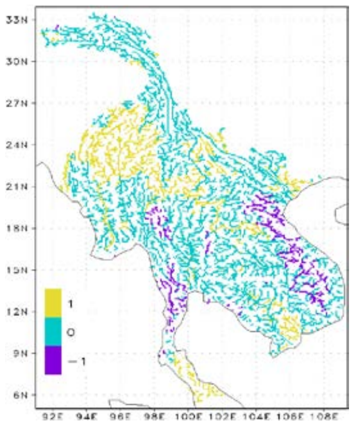
(b) YS_60_CMIP



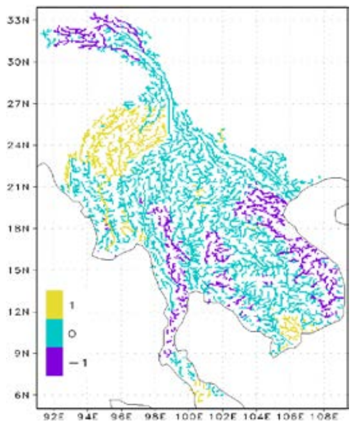
(c) KF_CMIP



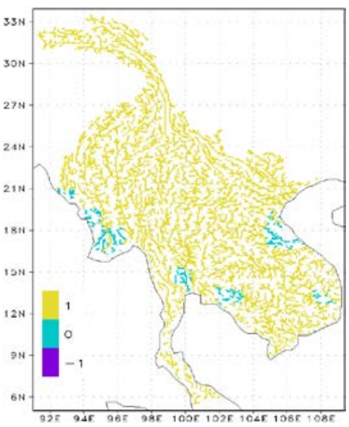
(d) KF_cluster1



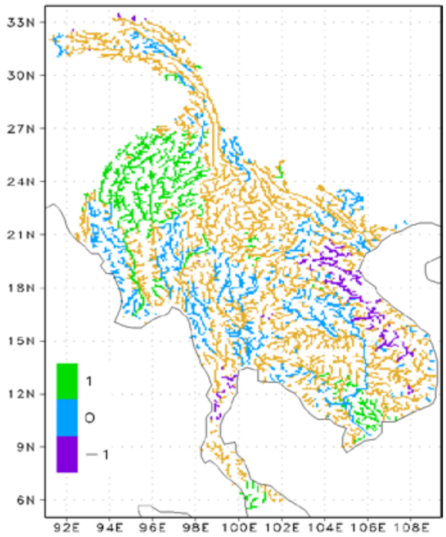
(e) KF_cluster2



(f) KF_cluster3



(g) MIROC5



(h) Combination of 6 simulations

Fig. 5.2 Statistical significance differences between annual mean discharge in the future climate experiment and in the present climate experiment

The color scale bar in Fig. 5.1 shows the ratio range corresponding to the color in each figure. The color index in Fig. 5.2 shows the statistical significance of changes in river discharge (1: increase and statistically significant; -1: decrease and statistically significant; 0: not significant). Fig 5.1h and Fig. 5.2h show the location where at least 4 out of 6 simulations have the same tendency in river discharge change or statistical significance (color index: 1 means "increase/significant" ; -1 means "decrease/significant"; 0 means "not so much change/not significant"). The simulation using MIROC5 dataset was not considered in the combination figure due to its too coarse spatial resolution (150-km).

From Fig. 5.1, it can be seen that there is an overall agreement between 6 ensemble experiments using MRI-AGCM datasets in the trend of annual mean discharge change in the Irrawaddy River basin, Salween River basin, upper most part of Red River basin, and central part of Vietnam. Most of the simulations using MRI-AGCM datasets show the increase in annual mean discharge in the Irrawaddy River basin and decrease in annual mean discharge in the central part of Vietnam. The changes in annual mean discharge in the Irrawaddy River basin and in the central part of Vietnam were also found statistically significant (see Fig. 5.2).

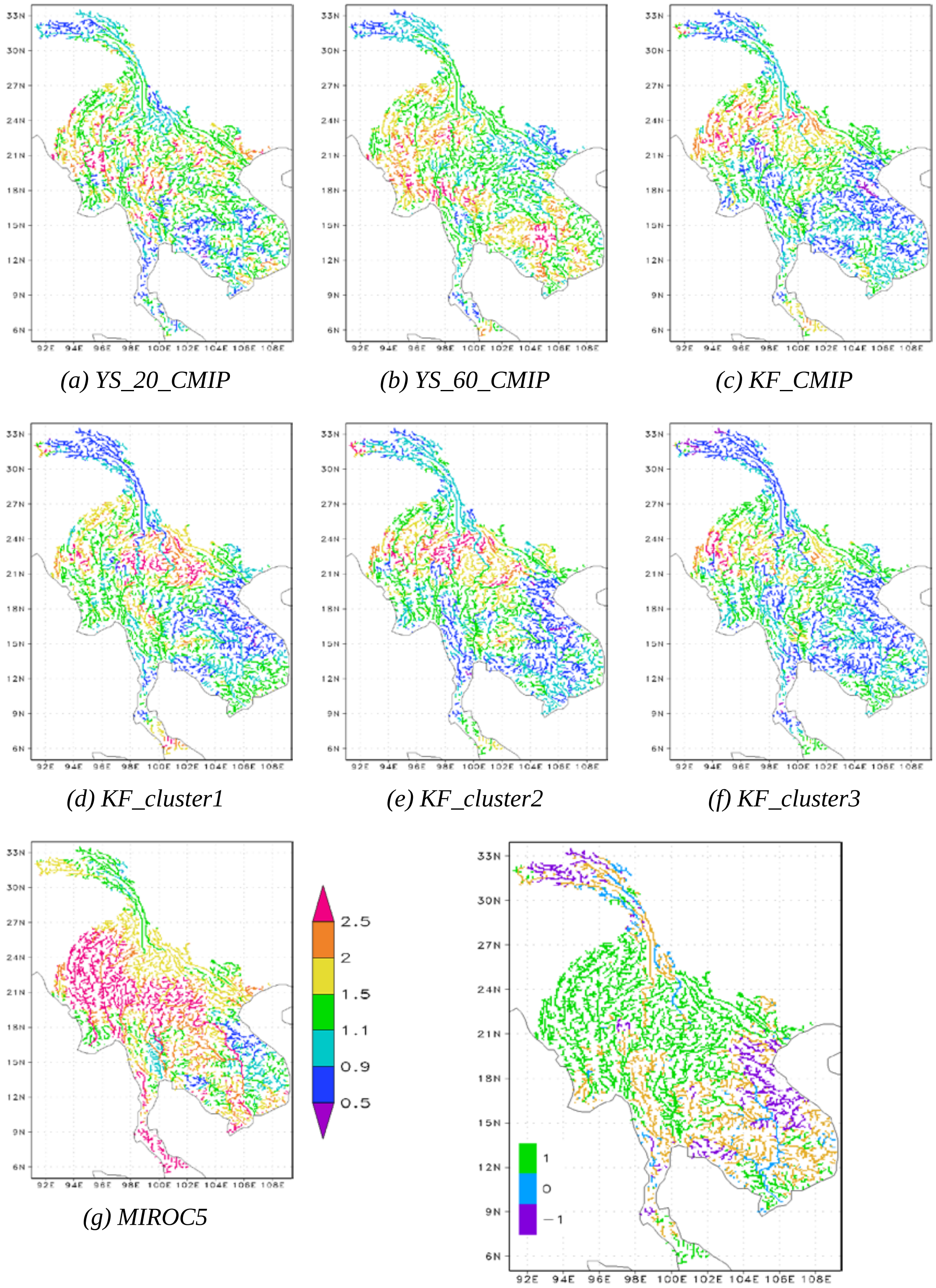
There are some uncertainties in river discharge projections between different ensemble experiments. The uncertainty due to differences in spatial resolution and cumulus schemes is larger than the uncertainty due to differences in SST patterns. YS_20_CMIP and YS_60_CMIP simulations used data from ensemble experiments having the same cumulus scheme and SST pattern, and different spatial resolution (20-km and 60-km). Over the most regions south of 19^{o}N (Chao Phraya River basin and lower part of Mekong River basin), the direction and ratio of changes in annual mean discharge are different (see Fig. 5.1a and Fig. 5.1b). The differences in statistical significances of changes in annual mean discharge are also visible in the lower part of Mekong River basin (see Fig. 5.2a and Fig. 5.2b).

The uncertainty due to difference in cumulus scheme can be examined by comparing results from YS_60_CMIP simulation and KF_CMIP simulation. These simulations used data from ensemble experiments with Yoshimura scheme and Kain-Fritsch scheme. Other parameters and settings are the same. Similar patterns in the changes in annual mean discharge were detected only in the Irrawaddy River basin and a small area in northern part of Vietnam. The statistical significance testing shows the differences in the upper most part of Red River basin, central part of Vietnam, and lower part of Mekong River basin.

For the simulations using ensemble experiments with the same cumulus scheme and different SSTs (KF_CMIP, KF_cluster1, KF_cluster2, and KF_cluster3), the future changes in annual mean discharge in the Indochina Peninsula region are generally consistent between four simulations (see Fig. 5.1c, d, e, and f).

5.3.2 Changes in mean of annual maximum daily discharge

Fig 5.3 and Fig. 5.4 show the relative change and statistical significance differences between mean of annual maximum daily discharge in the future climate and in the present climate.

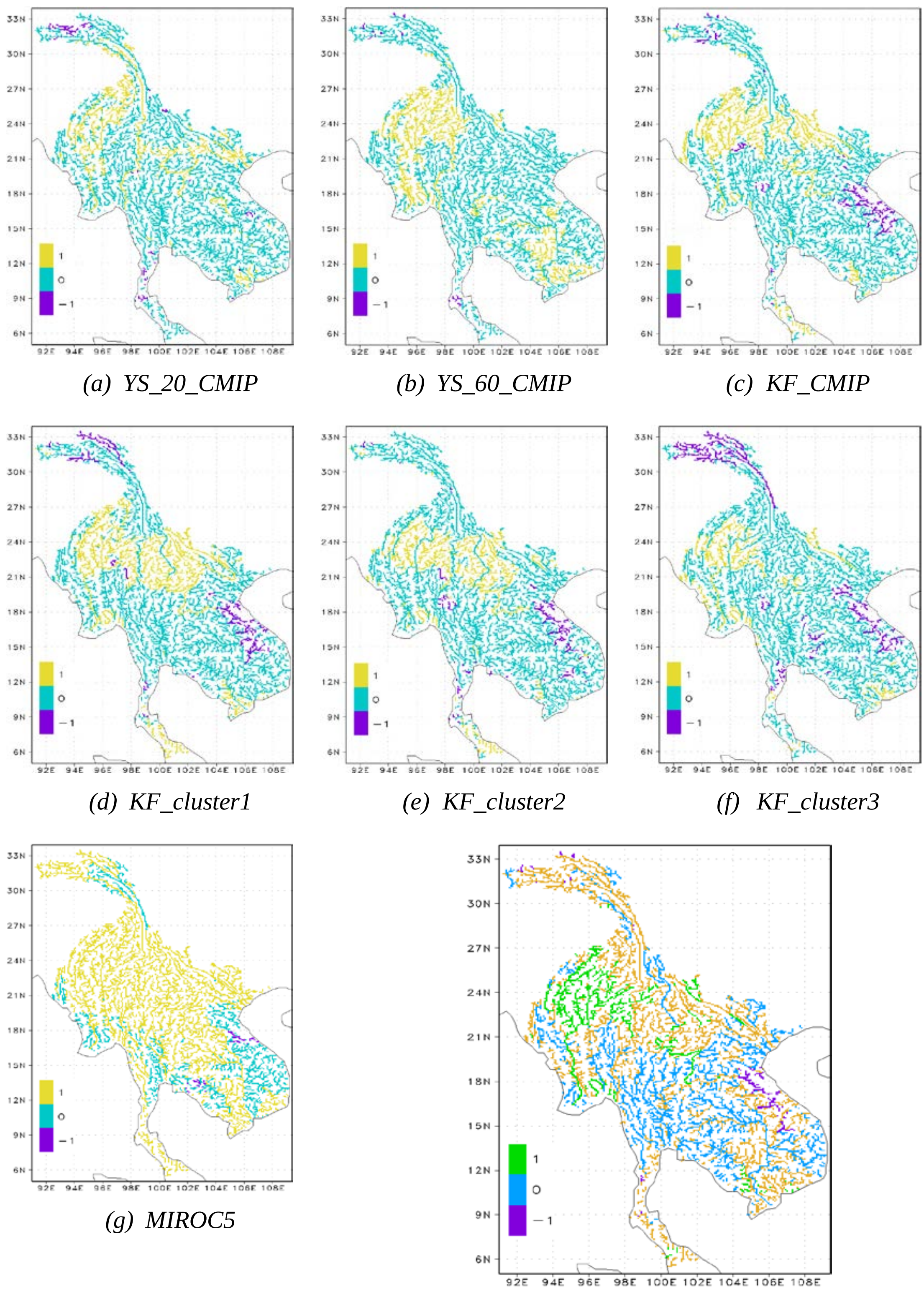


(a) YS_20_CMIP *(b) YS_60_CMIP* *(c) KF_CMIP*

(d) KF_cluster1 *(e) KF_cluster2* *(f) KF_cluster3*

(g) MIROC5 *(h) Combination of 6 simulations*

Fig. 5.3 Ratio of mean of annual maximum daily discharge in the future climate experiment to the one in the present climate experiment



(a) YS_20_CMIP *(b) YS_60_CMIP* *(c) KF_CMIP*

(d) KF_cluster1 *(e) KF_cluster2* *(f) KF_cluster3*

(g) MIROC5 *(h) Combination of 6 simulations*

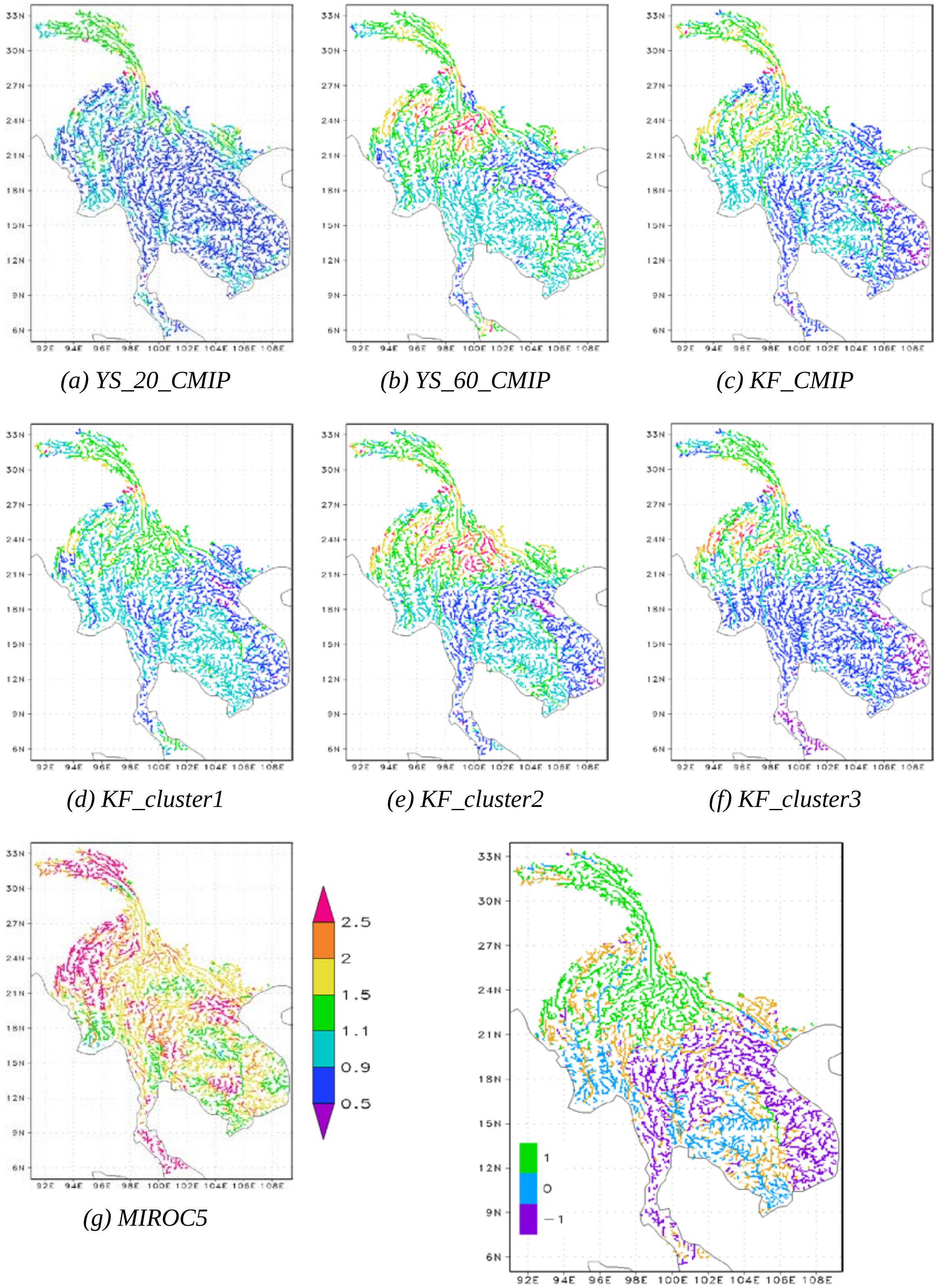
Fig. 5.4 Statistical significance differences between mean of annual maximum daily discharge in the future climate experiment and in the present climate experiment

The future increase in mean of annual maximum daily discharge was detected in the Irrawaddy River basin, in the middle part of Mekong River basin, and in the Red River basin in all simulations. The ratio of change in mean of annual maximum discharge is higher than the ratio of change in annual mean discharge. The decrease in mean of annual maximum daily discharge appeared in the upper most part of Mekong River basin and Salween River basin, and in the central part of Vietnam in at least four out of six simulations. However, the changes in mean of annual maximum daily discharge were commonly found statistically significant only at Irrawaddy River Basin and a small area in the central of Vietnam.

Regarding to the uncertainty, the variability of future changes in mean of annual maximum daily discharge between simulations using ensemble experiments with only different in future SST patterns is relatively small (see Fig. 5.3c, d, e, and f). In contrast, the differences in mean of annual maximum daily discharge changes projected using ensemble experiments with different cumulus schemes is considerably larger. While the simulation using Yoshimura scheme (YS_60_CMIP) shows the increase in annual maximum daily discharge on the right side of the study area, the simulation using Kain-Fritsch scheme shows the decrease (KF_CMIP).

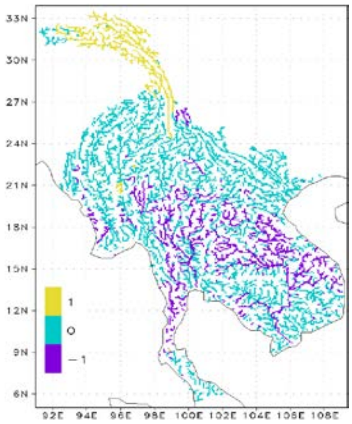
5.3.3 Changes in mean of annual minimum daily discharge

The relative change and statistical significance differences between mean of annual minimum daily discharge in the future climate and in the present climate are showed in Fig. 5.5 and Fig. 5.6.

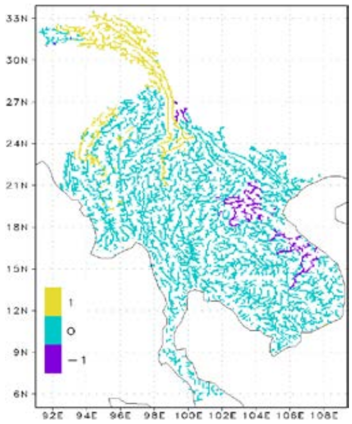


(h) Combination of 6 simulations

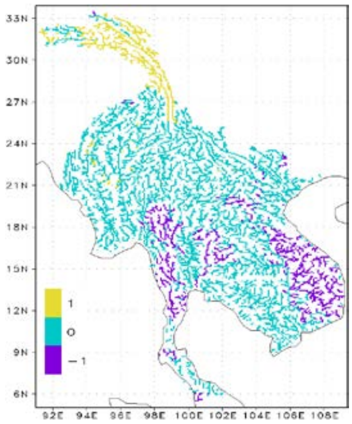
Fig. 5.5 Ratio of mean of annual minimum daily discharge in the future climate to the one in the present climate



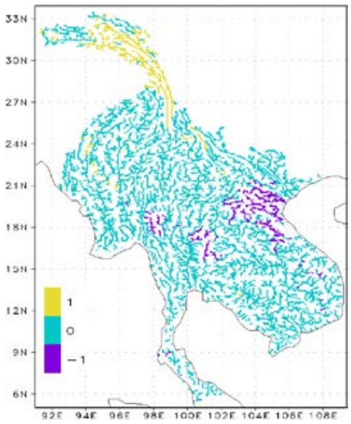
(a) YS_20_CMIP



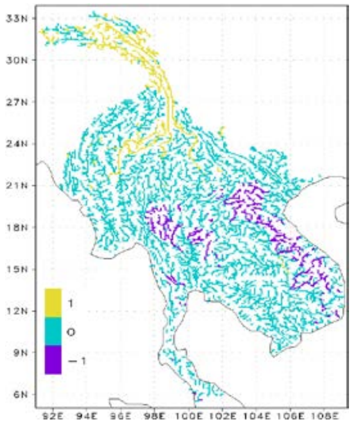
(b) YS_60_CMIP



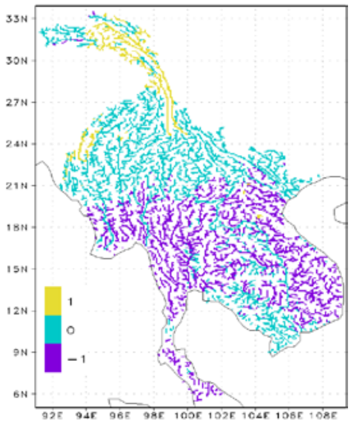
(c) KF_CMIP



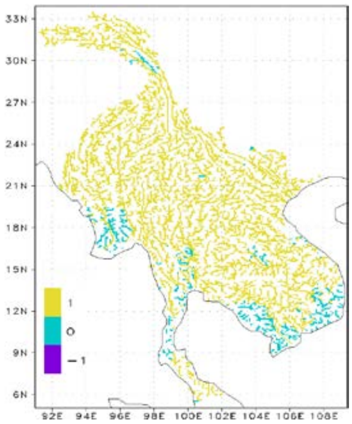
(d) KF_cluster1



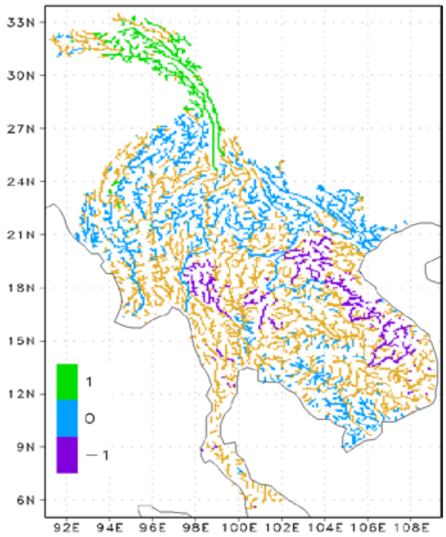
(e) KF_cluster2



(f) KF_cluster3



(g) MIROC5



(h) Combination of 6 simulations

Fig. 5.6 Statistical significance differences between mean of annual minimum daily discharge in the future climate and in the present climate

For the mean of annual minimum daily discharge, most of the simulations show an increasing trend in the Salween River basin and in the upper most part of Mekong River basin. Only the simulation using data from 20-km model shows the opposite result in this area (see Fig 5.5). Five out of six simulations have a decreasing trend in mean of annual minimum daily discharge in the north-western part of Chao Phraya River basin, and in the central and southern part of Vietnam. The changes in mean of annual minimum daily discharge were also confirmed statistically significant in the upper most part of Mekong River basin and Salween River basin, in north-western part of Chao Phraya River basin, and in the central part of Vietnam as illustrated in Fig. 5.6.

River discharge projected using MIROC5 dataset shows a marked difference in comparison with other simulations. The mean of annual minimum daily discharge was found statistically significant increase in almost entire Indochina Peninsula region (see Fig 5.5g and Fig. 5.6g). The increase of projected river discharge in MIROC5 simulation result is also much higher than in others. The same situation was experienced when examine the changes in annual mean discharge and mean of annual maximum daily discharge. These discrepancies may be contributed by the differences between MIROC5 and MRI-AGCM datasets: model structure, cumulus convection scheme, and especially spatial resolution. The spatial resolution of output from MIROC5 dataset is quite coarse, about 150-km. It is generally not considered of a sufficient resolution to be applied directly in hydrological impact studies.

5.4. Conclusions

This chapter investigated the change in river discharge in the Indochina Peninsula region under a changing climate using distributed flow routing model 1K-FRM and 10 ensemble experiments from three different GCM datasets (MRI-AGCM3.2S, MRI-AGCM3.2H, and MIROC5). Statistical analysis was carried out to examine the statistical significance of river discharge changes in the region. The uncertainty in river discharge projected using ensemble experiments with different cumulus convection schemes and SST patterns was also discussed.

Using different ensemble experiments result in different projections of river discharge change in the Indochina Peninsula region. However, there is a strong agreement between these ensembles on the increase in annual mean discharge and mean of annual maximum daily discharge in the Irrawaddy River basin, and the increase in mean of annual minimum daily discharge in the upper most part of the Salween River basin and Mekong River basin. In addition, a large majority of simulation results show a decrease in annual mean discharge and mean of annual minimum daily discharge in the central part of Vietnam.

For the uncertainty in river discharge projection, the results indicate that the uncertainty arising from the differences in cumulus convection schemes and spatial resolution is much larger than the uncertainty sourced from changing SST patterns.

References

Dobler, C., Hagemann, S., Wilby, R. L. and Stötter, J. (2012) Quantifying different sources of uncertainty in hydrological projections in an Alpine watershed, *Hydrol. Earth Syst. Sc.*, 16(11), 4343–4360.

Endo, H., A. Kitoh, T. Ose, R. Mizuta, and S. Kusunoki (2012), Future changes and uncertainties in Asian precipitation simulated by multiphysics and multi–sea surface temperature ensemble experiments with high-resolution Meteorological Research Institute atmospheric general circulation models (MRI-AGCMs), *J. Geophys. Res.*, 117, D16118.

Gosling, S. N., Taylor, R. G., Arnell, N. W., and Todd, M. C. (2011) A comparative analysis of projected impacts of climate change on river runoff from global and catchment-scale hydrological models, *Hydrol. Earth Syst. Sci.*, 15, 279–294.

Gualdi S., S. Somot, W. May, S. Castellari, Michel Deque, M. Adani, V. Artale, A Bellucci and Co-authors, 2011. Future Climate Projections in Regional Assessment of Climate Change in the Mediterranean. A. Navarra, L.Tubiana (eds.), *Springer, Dordrecht, The Netherlands*.

Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai (2013) Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

[Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.*

Hawkins, E. and Sutton, R. (2009) The Potential to Narrow Uncertainty in Regional Climate Predictions, *B. Am. Meteorol. Soc.*, 90, 1095–1107.

Jin Teng, Jai Vaze, Francis H. S. Chiew, Biao Wang, and Jean-Michel Perraud (2012) Estimating the Relative Uncertainties Sourced from GCMs and Hydrological Models in Modeling Climate Change Impact on Runoff. *J. Hydrometeor*, 13, 122–139.

Kay, A. L., H. N. Davies, V. A. Bell, and R. G. Jones (2009) Comparison of uncertainty sources for climate change impacts: Flood frequency in England. *Climatic Change*, 92, 41–63.

Knutti, R. and J. Sedlacek (2013) Robustness and uncertainties in the new CMIP5 climate model projections, *Nature Climate Change*, 3, 369–373.

Kitoh, A., T. Ose, K. Kurihara, S. Kusunoki, M. Sugi, and KAKUSHIN Team-3 Modeling Group (2009) Projection of changes in future weather extremes using super-high-resolution global and regional atmospheric models in the KAKUSHIN Program: Results of preliminary experiments. *Hydrological Research Letters*, 3, 49–53.

Mizuta, R., Y. Adachi, S. Yukimoto, and S. Kusunoki (2008) Estimation of the future distribution of sea surface temperature and sea ice using the CMIP3 multi-model ensemble mean, Tech. Rep. 56, 28 pp., *Meteorol. Res. Inst., Tsukuba, Japan*.

Murakami, H., R. Mizuta, and E. Shindo (2012a) Future changes in tropical cyclone activity projected by multi-physics and multi-SST ensemble experiments using the 60-km-mesh MRI-AGCM, *Clim. Dyn*.

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP (2003) Global analysis of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J Geophys Res* 108:4407.

Watanabe, M., Suzuki, T., Oishi, R., Komuro, Y., Watanabe, S., Emori, S., Takemura, T., Chikira, M., Ogura, T., Sekiguchi, M., Takata, K., Yamazaki, D., Yokohata, T., Nozawa, T., Hasumi, H., Tatebe, H., Kimoto, M.: Improved climate simulation by MIROC5 (2010) Mean states, variability, and climate sensitivity, *Journal of Climate*, 23, 6312–6335.

Chapter 6

Bias correction of runoff generation data to improve river discharge projection

6.1 Introduction

Climate change is now widely accepted as a scientific fact. It is projected to have significant impacts on hydrology and water resources. The most common approach to assess the hydrological impacts of global climate change is to force hydrological models (HMs) or land surface models (LSMs) with output from general circulation models (GCMs). Therefore, the quality of hydrological impact investigations largely depends on the accuracy of GCMs in simulating climate data (Hagemann et al., 2011).

Although there are considerable improvements in the performance of GCMs in recent years, outputs of GCMs still suffer from systematic errors, or biases, which can be due to:

- Incomplete knowledge of climate system processes
- Numerical schemes
- Parameterizations of small scale (sub-grid scale) processes
- Coarse spatial resolution

Removing these biases in GCM outputs is therefore essential for improving the reliability of climate projections and hydrological simulations forced by climate model data. Several bias correction methods have been developed and received much attention in climate change impacts studies (e.g. Themeßl et al., 2011; Hagemann et al., 2011; Teutschbein and Seibert, 2012).

In the previous chapters, river discharge in the Indochina Peninsula region was projected by feeding the GCM runoff generation data into flow routing model 1K-FRM. Output from flow routing model was used to examine the future changes in river discharge in the region under a changing climate. To improve the projection of river discharge using 1K-FRM, in this chapter, bias correction is considered to apply to GCM runoff generation data.

6.2 Methods

GCM runoff generation data used for river discharge projection were simulated by a land surface model embedded in the GCM. In MRI-AGCM, for example, land surface model Simple Biosphere (SiB; Sellers et al., 1986) was used. Due to the unavailability of observed runoff generation data, an advanced land surface process model called Simple Biosphere including Urban Canopy (SiBUC; Tanaka, 2005) was applied to reproduce runoff generation data based on meteorological and phenological records. Output of SiBUC model was used as reference data for bias correction of GCM runoff generation data. Biases in GCM runoff generation data were corrected using quantile-quantile mapping bias correction method.

In this work, river discharge were simulated using flow routing model 1K-FRM with MRI-AGCM3.2S runoff generation data, SiBUC runoff generation data, and bias-corrected runoff generation data. Results from these simulations were compared to examine the performance of land surface process model and bias correction method in river discharge projection.

6.3 Study area

The target study area is the Indochina Peninsula region, which is quite large. Therefore, it is better to verify the feasibility of the proposed method with some small basins. The analysis in this study was performed for two river basins in Kyushu area, Japan – Chikugo River basin and Oyodo River basin. Fig. 6.1 shows the location of these two river basins.

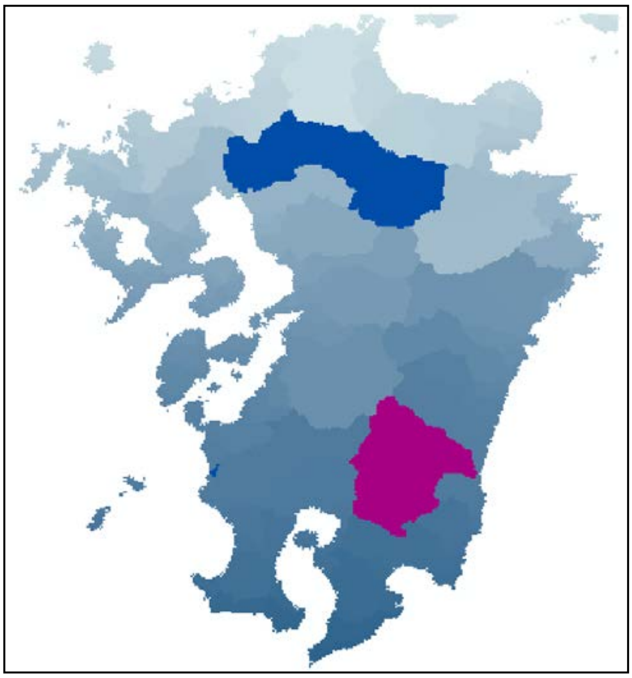


Fig. 6.1 Location of Chikugo River basin (blue) and Oyodo River basin (red) in Kyushu area, Japan

Chikugo River flows through Oita, Fukuoka, Kumamoto, and Saga prefectures in Kyushu area, Japan. With a total length of about 143 km, it is the longest river on Kyushu Island. The total basin area of Chikugo River is about 2,800 km^2.

Oyodo River runs through Kagoshima prefecture and Miyazaki prefectures with the basin area of about 2,230 km^2. The length of Oyodo River basin is about 107 km.

6.4 Land surface process model

The land surface process model Simple Biosphere including Urban Canopy (SiBUC) was presented by Tanaka (2005) in Disaster Prevention Research Institute, Kyoto University. SiBUC model uses mosaic approach, which couples independently each land-use patch of the grid element to the atmosphere, to incorporate all kind of land-use to land surface scheme.

In SiBUC model, the surface of each grid cell is divided into three land-use categories including green area (vegetation canopy and ground), urban area (urban canopy and urban ground), and water body. Fig. 6.2 shows the schematic image of surface elements in SiBUC model.

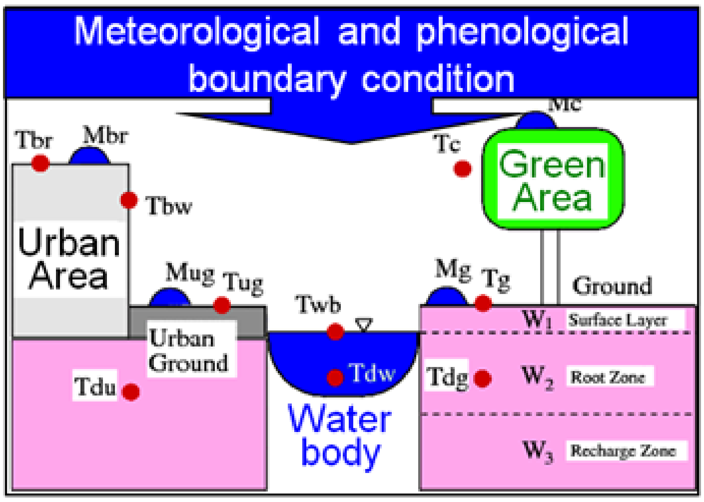


Fig. 6.2 Schematic image of surface elements in SiBUC model

The fractions of these three land-use categories are fixed for each grid cell in SiBUC model. And surface fluxes are obtained by averaging the surface fluxes over each land-use weighted by its fractional area.

6.5 Data

6.5.1 Topographic data

The topographic data used in flow routing model 1K-FRM and land surface process model for two river basins in Kyushu area were the 30 arc-second (1-km) DEM and flow direction stored in HydroSHEDS (Lehner, 2006) for Asian regions. HydroSHEDS (Hydrological data and maps based on Shuttle Elevation Derivatives at multiple scales) provides hydrographic information for region and global-scale applications based on high-resolution elevation data obtained by NASA’s Shuttle Radar Topography Mission.

6.5.2. GCM runoff generation data

GCM data used for flow routing model 1K-FRM to project river discharge were 3-hourly runoff generation data from super-high-resolution (20-km) atmospheric general circulation model MRI-AGCM3.2S with three climate experiments: the present climate experiment (1979-2008), the near future climate experiment (2015-2044), and the future climate experiment (2075-2104).

6.5.3. Meteorological data

Meteorological data to force land surface process model SiBUC include seven components: precipitation, air temperature, specific humidity, surface pressure, wind speed, long wave radiation, and short wave radiation. In this study, the product of the Japanese 55-year reanalysis (JRA-55) project was utilized to use as inputs for SiBUC. However, JRA-55 precipitation and surface radiation data are forecast data, not reanalysis data. Therefore, other data sources were considered to use as substitution. For precipitation data, the Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE's Water Resources) project was selected. And the Surface Radiation Budget (SRB) dataset was used to process long wave radiation and short wave radiation data.

JRA-55 reanalysis data

The Japanese 55-year Reanalysis (JRA-55) is the second reanalysis project conducted by Japan Meteorological Agency (JMA) (Ebita et al., 2011). In this project, a sophisticated data assimilation system based on the operational system as of December 2009 and newly prepared dataset of past observations were used to produce a high-quality homogeneous climate dataset. The analysis period covers 50 years from 1958, when regular radiosonde observation began on a global basis. Table 6.1 and Table 6.2 summary information about JRA-55 meteorological data used for land surface process model SiBUC.

Table 6.1 Parameters of surface analysis fields

Field parameter	Unit	Level
Pressure	Pa	Ground or water surface
Temperature	K	2m
Specific humidity	kg kg^{-1}	2m
u-component of wind	m s^{-1}	10m
v-component of wind	m s^{-1}	10m

Table 6.2 Parameters of two-dimensional average diagnostic fields

Field parameter	Unit	Level
Total precipitation	mm day^{-1}	Ground or water surface
Downward solar radiation flux	W m^{-2}	Ground or water surface
Downward long wave radiation flux	W m^{-2}	Ground or water surface

The spatial resolution of JRA-55 data is 0.5625 degree. Parameters of surface analysis fields have 6-hour temporal resolution. And parameters of two-dimensional average diagnostic fields have 3-hour temporal resolution.

APHRODITE's Water Resources data

The Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE's Water Resources) project was conducted by the Research Institute for Human and Nature (RIHN) and the

Meteorological Research Institute of Japan Meteorological Agency (MRI/JMA) from 2006 to develop state-of-the-art daily precipitation datasets on high-resolution grids covering the whole of Asia (Yatagai et al., 2012). The datasets are created primarily with data obtained from a rain gauge observation network. The APHRODITE's Water Resources dataset is the only long-term continental-scale daily product that contains a dense network of daily rain-gauge data for Asia, especially Japan. The distribution of rain gauge stations is shown in Fig. 6.3.

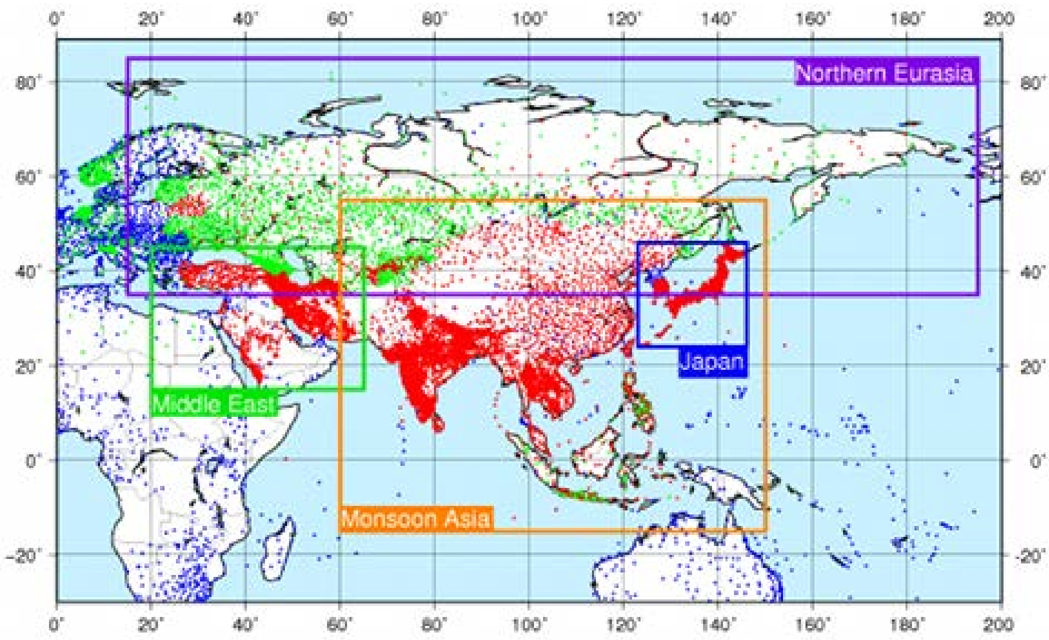


Fig. 6.3 Distribution of collected rain gauge station in APHRODITE's Water Resources project (Source: http://www.chikyu.ac.jp/precip/products/index.html)

Precipitation data to force land surface process model for Kuyshu area was extracted from the APHRO_JP V1207 (Kamiguchi et al., 2010) dataset with spatial resolution of 0.05 degree. Temporal resolution of APHRO_JP precipitation data is daily.

Surface Radiation Budget data

Surface Radiation Budget (SRB) dataset is produced and archived by the NASA Langley Research Center Atmospheric Sciences Data Center (NASA/GEWEX). It is produced on a 1 degree x 1 degree global grid using satellite-derived cloud parameters and ozone fields, reanalysis meteorology, and a few other ancillary datasets. The SRB dataset contains 3-hourly long wave and short wave radiative fluxes.

6.5.4 Soil, vegetation, and land use data

Phenological boundary conditions related to soil type, vegetation type and land use data for Kyushu area in SiBUC model were collected from Ministry of Land, Infrastructure, Transport and Tourism (MLIT, Japan) field survey data and satellite databases such as ECOCLIMAP product and GLASS Leaf Area Index product.

Land use data

Land use data for Kyushu area collected from MLIT consist of 16 categories including paddy, farmland, fruit farm, other farm, forest, waste land, building A, building B, road, other land, lake, river A, river B, beach, and unknown. Surface parameters related to land use for green area, urban area, and water body in SiBUC model was set based on this category. The spatial resolution of MLIT land use data is 100 m.

Vegetation data

Parameters for vegetation type were derived from the GLASS Leaf Area Index (LAI) product, which generated by the Center for Global Change Data Processing and Analysis of Beijing Normal University (Xiao et al., 2013). The GLASS product is available from 1982 to 2012 with temporal resolution of 8 days and spatial resolution of 0.05 degree.

Soil data

Soil parameters in SiBUC model such as root depth, soil depth, soil texture class, etc. were set baed on ECOCLIMAP product (Masson et al., 2003). ECOCLIMAP is a database of surface parameters at 1-km resolution which was implemented in the METEO-FRANCE operation models.

6.5.5 Resolution and simulation period of SiBUC model

The output data grid of SiBUC was set in the same coordinate, spatial resolution as MRI-AGCM3.2S runoff generation data. Input data with finer spatial resolution such as soil and vegetation were aggregated to create 20-km spatial resolution data. For coarser spatial resolution data, value of the nearest grid was selected in calculation.

SiBUC model was set to simulate runoff in Kyushu area for 1982-2010 period based on the availability of input data.

6.6 Bias correction of GCM runoff generation data

To correct biases in GCM runoff generation data, quantile-quantile mapping (QQM) bias correction method was selected. QQM was first introduced by Brier and Panofsky (1968) as empirical transformation. Methods based on quantile mapping are getting more popular and widely used to correct climate model outputs (e.g. Leimer et al., 2011; Vidal and Wade, 2008). Themeßl et al. (2011) and Teutschbein and Seibert (2012) compared various bias correction methods and showed that QQM performs better than others.

In QQM bias correction method, GCM output and observations are sorted for the same historical base period to construct cumulative distribution functions (CDFs). These CDFs is used to define the quantiles of simulated values and observations. Then, GCM simulated values is substituted with those of the identical quantile from the observational dataset. Fig. 6.4 shows the schematic representation of quantile-quantile mapping.

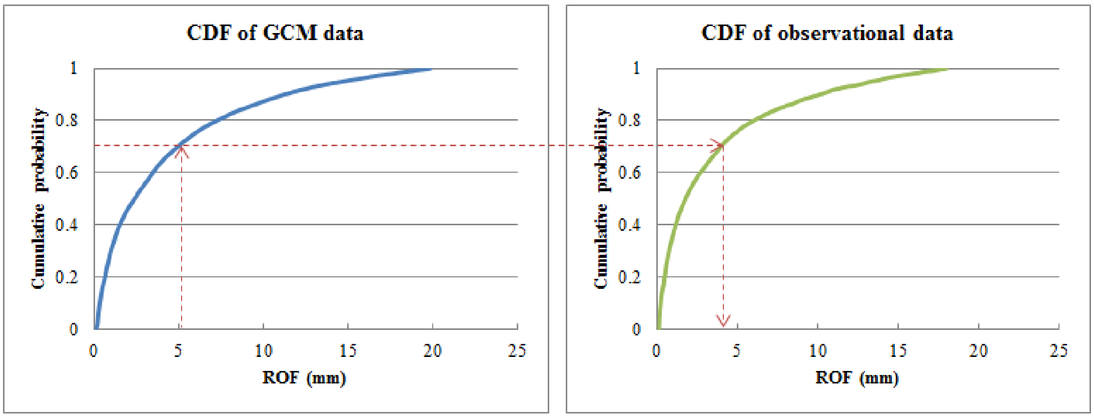


Fig. 6.4 Schematic representation of quantile-quantile mapping

In this study, runoff data simulated by SiBUC model were used as reference data to correct MRI-AGCM3.2S runoff generation data. Bias correction was applied to MRI-AGCM3.2S runoff generation data at each grid cell as follows:

- Runoff generation data from MRI-AGCM3.2S dataset and SiBUC model at the same grid and in the same calendar month for the whole simulation period were sorted from smallest to largest to construct cumulative distribution functions.
- Runoff generation data from MRI-AGCM3.2S dataset at each quantile was corrected by SiBUC runoff data at the equivalent quantile.
- MRI-AGCM3.2S corrected runoff generation data were rearranged following the original time order.

6.7 Results and discussions

6.7.1 Reproduction of runoff generation data using SiBUC

Two simulations for Kyushu area were carried out using SiBUC model with different precipitation data sources, JRA-55 and APHRO_JP. Fig. 6.5 shows the annual mean runoff in Kyushu area simulated by SiBUC model. Simulation using APHRO_JP precipitation data shows a higher value of annual mean runoff compared to the one using JRA-55 precipitation data.

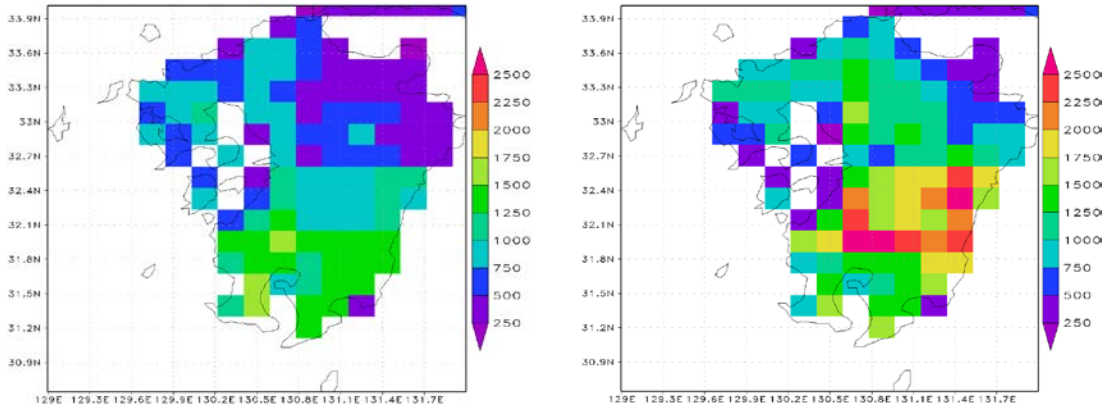


Fig. 6.5 Annual mean runoff in Kyushu area simulated using JRA-55 (left) and APHRO_JP precipitation data (right) from 1982-2008 (unit: mm/year)

To examine the reproduction of runoff generation data using land surface process model, river discharge in Kyushu area were simulated using runoff generation data given by SiBUC model. The runoff data simulated by SiBUC model using JRA-55 and APHRO_JP precipitation data hereinafter referred to as JRA-55 runoff data and APHRO_JP runoff data.

Flow duration curves for Oyodo River at Takaoka station and for Chikugo River at Senoshita station were constructed using the total-period method and the calendar-year method to compare simulated discharge with observations. Observational data at two stations mentioned above are available for 20 years period, from 1982 to 2001.

Fig. 6.6 and Fig. 6.7 show the total period and calendar-year flow duration curves for daily flow at Takaoka station, Oyodo River. Flow duration curves for Chikugo River at Senoshita are illustrated in Fig. 6.8 and Fig. 6.9 respectively.

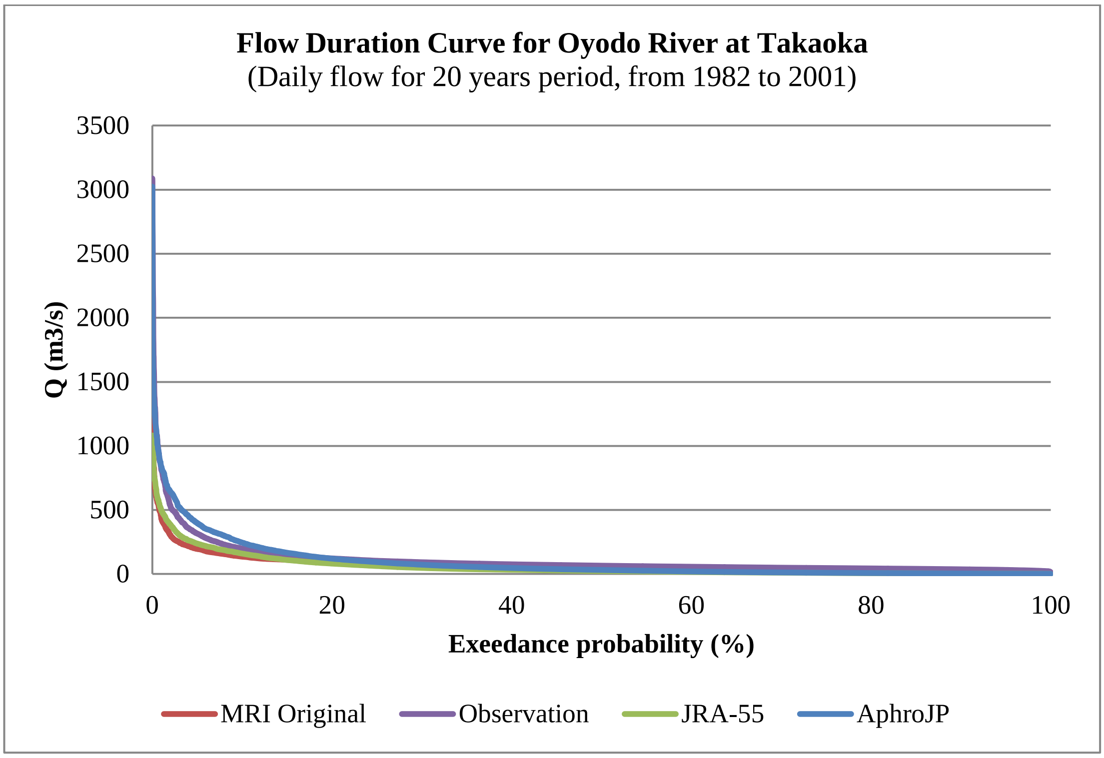


Fig. 6.6 Total period flow duration curve of daily flow for Oyodo River at Takaoka

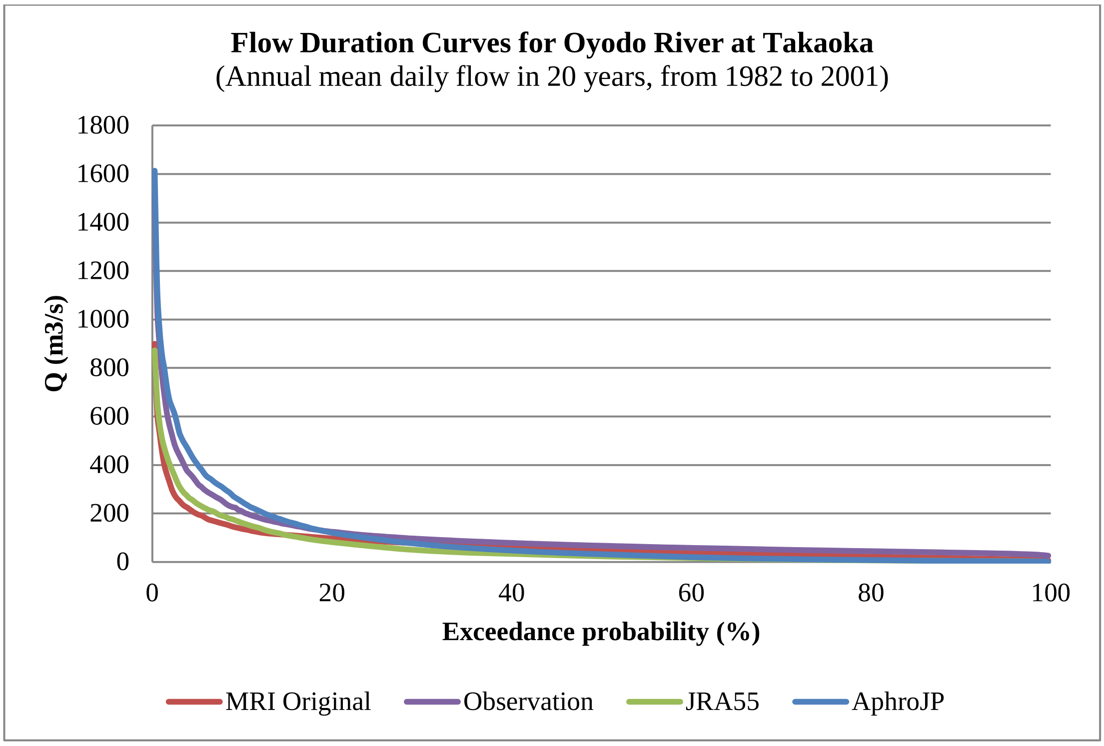


Fig. 6.7 Calendar-year flow duration curve of daily flow for Oyodo River at Takaoka

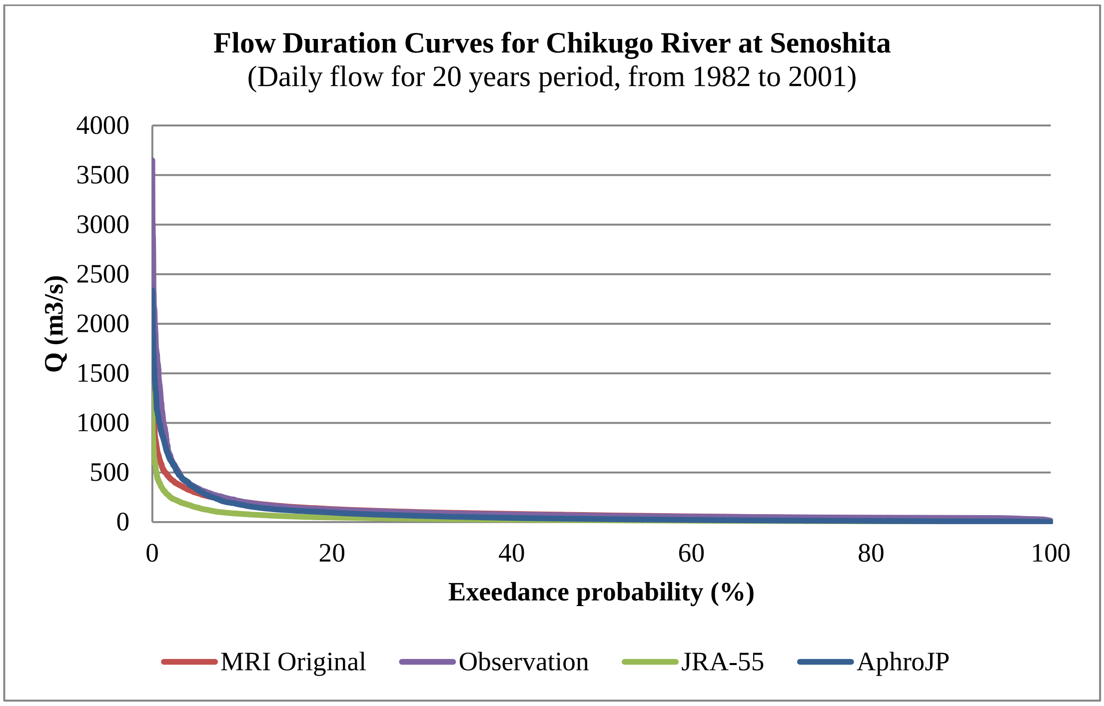


Fig. 6.8 Total period flow duration curve of daily flow for Chikugo River at Senoshita

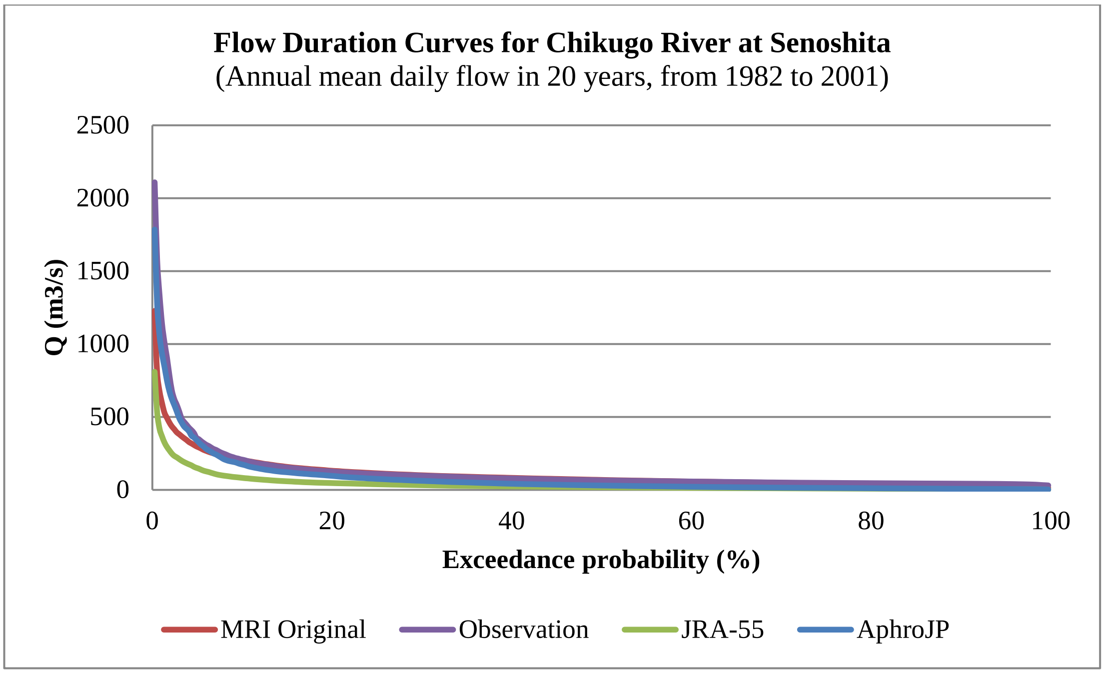


Fig. 6.9 Calendar-year flow duration curve of daily flow for Chikugo River at Senoshita

As can be seen in Fig. 6.6, the flow duration curve from simulation using APHRO_JP runoff data was more close to observed data at Takaoka station, Oyodo River basin. River discharges simulated using original MRI runoff generation data and JRA-55 runoff data are lower than the observations. The calendar-year flow duration curves show similar pattern as the total-period flow duration curves (see Fig. 6.7).

At Senoshita station, Chikugo River basin, although all the simulation showed an underestimation of the simulated river discharges from the observation, the simulation using APHRO_JP runoff data still performs better than others (see Fig. 6.8 and Fig. 6.9). Therefore, in bias correction part, APHRO_JP runoff data were chosen as reference data to correct biases in MRI-AGCM3.2S runoff generation data.

6.7.2 Bias correction of runoff generation data

Biases in MRI-AGCM3.2S runoff generation data were corrected with APHRO_JP runoff data using quantile-quantile mapping method. Corrected MRI-AGCM3.2S runoff generation data were fed into flow routing model 1K-FRM to examine the effect of bias correction of runoff generation data on river discharge simulation.

Fig. 6.10 shows an example of the time series of MRI-AGCM3.2S runoff generation data, APHRO_JP runoff data, and corrected runoff generation data for 20 years period (1982-2001) at one grid upstream of Takaoka station, Oyodo River basin.

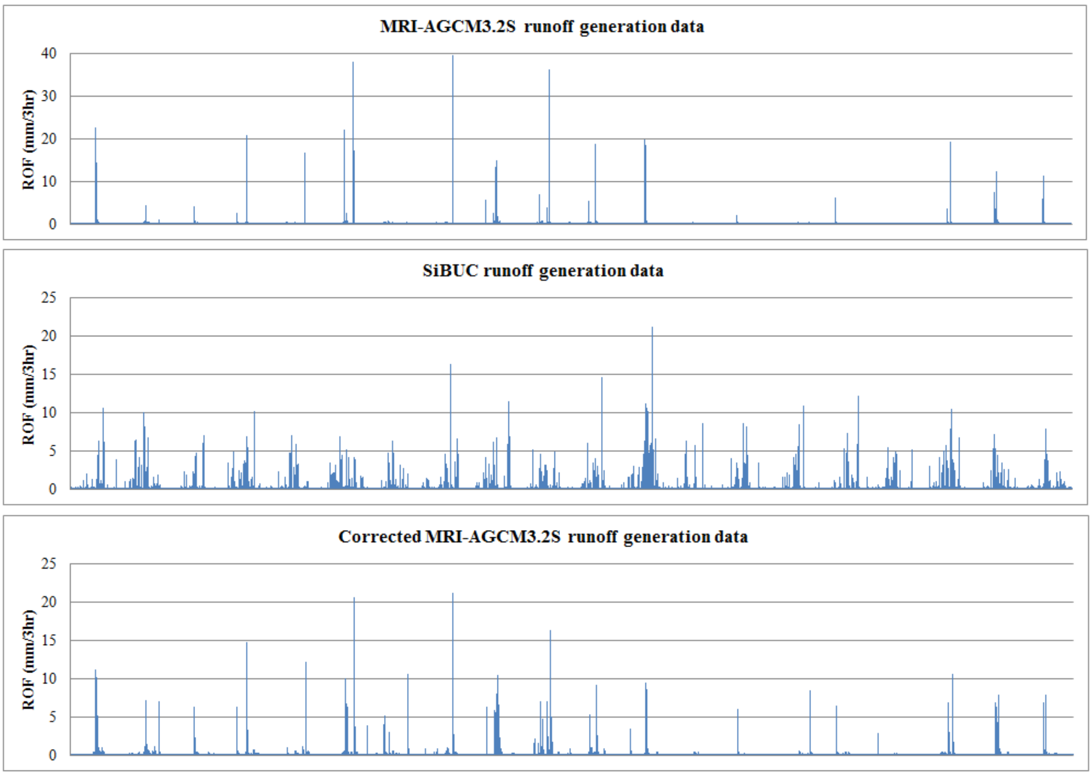


Fig. 6.10 An example of time series of runoff generation data for 20 years period (1982-2001)

It can be seen that, after bias correction, the temporal distribution pattern of corrected runoff generation data is similar to that of original MRI-AGCM3.2S data. However, comparing to reference data, the number of events with high runoff depth in the corrected runoff generation data is smaller but the density of high runoff depth in each event is higher. It may result in less flood events but higher peak discharge values.

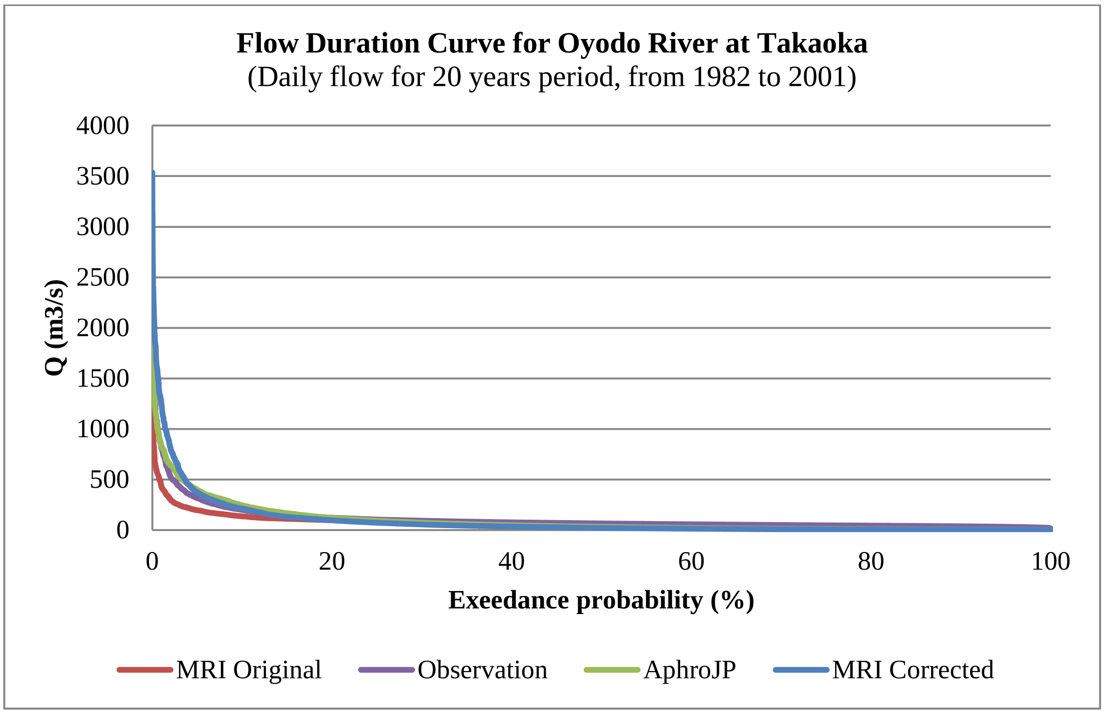


Fig. 6.11 Total period flow duration curve of daily flow for Oyodo River at Takaoka

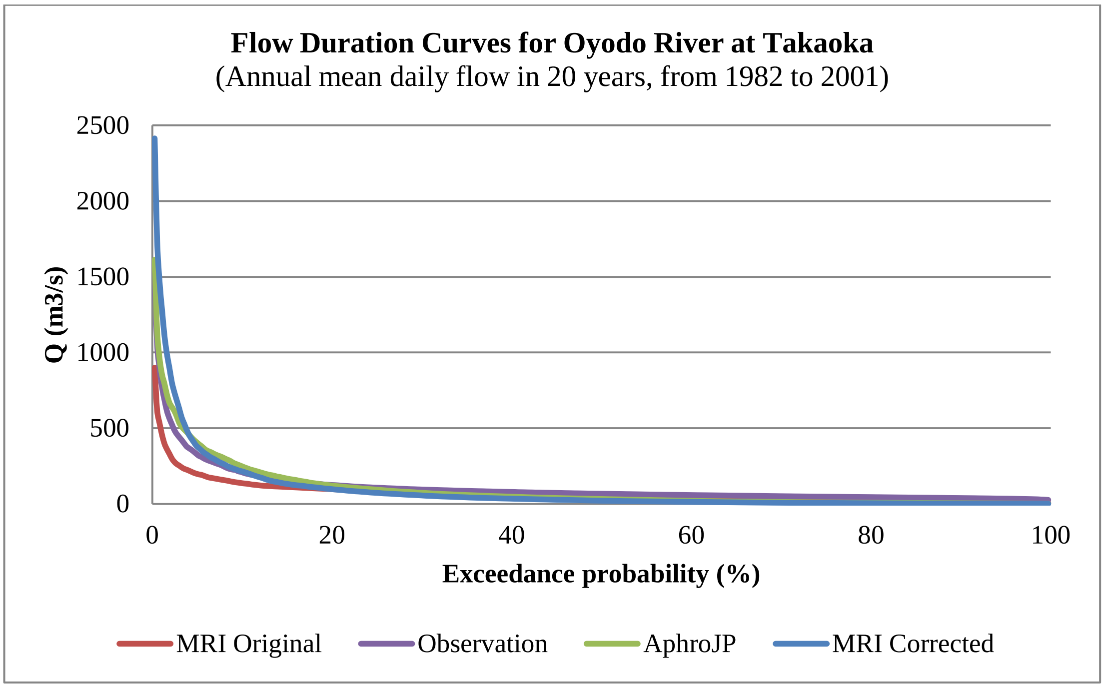


Fig. 6.12 Calendar-year flow duration curve of daily flow for Oyodo River at Takaoka

Flow duration curves for river discharge simulated using corrected runoff generation data at Takaoka station, Oyodo River basin, are illustrated in Fig. 6.11 and Fig. 6.12. River discharge simulated using bias-corrected runoff generation data show an improvement comparing to original MRI-AGCM3.2S data. However, the peak discharge values are overestimated in comparison with simulation using reference runoff generation data. It may arise from the differences in temporal distribution pattern between corrected runoff generation data and reference data as mentioned above.

6.8 Conclusions

In this study, runoff generation data in the Kyushu area were simulated using a land surface process model SiBUC with reanalysis data. It was used as reference data to correct biases in MRI-AGCM3.2S runoff generation data.

SiBUC model showed a good performance in reproducing runoff generation data for Kyushu area. If high quality observed data are available, land surface process model will be a useful tool to reproduce runoff for a long-term period.

Bias correction of MRI-AGCM3.2S runoff generation data were also performed and showed an improvement in river discharge simulations. However, further works need to be done in bias correction of runoff generation data considering their temporal distribution pattern to improve river discharge projection. The spatial and temporal correlation of runoff generation data between neighbour grid-cells should also be considered.

References

Brier W, Panofsky H (1968) Some applications of statistics to meteorology. *Mineral Industries Extension Services, School of Mineral Industries, Pennsylvania State College*.

Ebita, A., S. Kobayashi, Y. Ota, M. Moriya, R. Kumabe, K. Onogi, Y. Harada, S. Yasui, K. Miyaoka, K. Takahashi, H. Kamahori, C. Kobayashi, H. Endo, M. Soma, Y. Oikawa, and T. Ishimizu (2011) The Japanese 55-year Reanalysis "JRA-55": an interim report, *SOLA*, 7, 149-152.

Hagemann, S., Chen, C., Haerter, J. O., Heinke, J., Gerten, D., and Piani, C. (2011) Impact of a statistical bias correction on the projected hydrological changes obtained from three GCMs and two hydrology models, *J. Hydrometeorol.*, 12, 556–578.

Kamiguchi, K., O. Arakawa, A. Kitoh, A. Yatagai, A. Hamada and N. Yasutomi (2010) Development of APHRO_JP, the first Japanese high-resolution daily precipitation product for more than 100 years. *Hydrological Research Letters*, 4: 60-64.

Lehner, B., Verdin, K., Jarvis, A. (2006) HydroSHEDS Technical Documentation. *World Wildlife Fund US, Washington, DC.* Available at http://hydrosheds.cr.usgs.gov.

Leimer, S., Pohlert, T., Pfahl, S., and Wilcke, W., (2011) Towards a new generation of high-resolution meteorological input data for small-scale hydrologic modeling. *Journal of Hydrology*, 402 (3-4): 317-332.

Sellers, P. J., Mintz, Y., Sud, Y. C. and Dalcher, A., (1986) A simple biosphere model (SiB) for use within general circulation models, *J. Atmos. Sci.*, 43,505-531.

Tanaka, K. (2005) Development of the new land surface scheme SiBUC commonly applicable to basin water management and numerical weather prediction model. *Doctoral thesis, Kyoto University*.

Themeßl, M. J., A. Gobiet, and A. Leuprecht (2011) Empiricalstatistical downscaling and error correction of daily precipitation from regional climate models. *Int. J. Climatol.*, 31, 1530–1544.

Teutschbein, C. and Seibert, J. (2012) Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods, *Journal of Hydrology*, vol. 456–457, pages 12-29.

Valéry Masson, Jean-Louis Champeaux, Fabrice Chauvin, Christelle Meriguet, and Roselyne Lacaze (2003) A Global Database of Land Surface Parameters at 1-km Resolution in Meteorological and Climate Models. *J. Climate*, 16, 1261–1282.

Vidal, J. P. and Wade, S. (2008) A framework for developing high-resolution multi-model climate projections: 21st century scenarios for the UK. *International Journal of Climatology*, 28 (7): 843-858.

Xiao Z., S. Liang, J. Wang, et al. (2013) Use of General Regression Neural Networks for Generating the GLASS Leaf Area Index Product from Time Series MODIS Surface Reflectance. *IEEE Transactions on Geoscience and Remote Sensing*.

Yatagai, A., K. Kamiguchi, O. Arakawa, A. Hamada, N. Yasutomi and A. Kitoh (2012) APHRODITE: Constructing a Long-term Daily Gridded Precipitation Dataset for Asia based on a Dense Network of Rain Gauges, *Bulletin of American Meteorological Society*.

Chapter 7

Conclusions

The main objectives of this study were as follows:

- ♦ To project river discharge in the Indochina Peninsula region using a distributed flow routing model and outputs from general circulation models.
- ♦ To examine potential changes in river discharge in the region under a changing climate.
- ♦ To analyze the statistical significance of river discharge changes in the Indochina Peninsula region to locate possible hotspot basins where significant changes related to floods, droughts or water resources could occur.
- ♦ To evaluate the uncertainties in the future climate projections by comparing simulations using ensemble experiments of different GCMs.
- ♦ To improve future projection of river discharge in the Indochina Peninsula region by bias corrections of runoff generation data.

In chapter 3, river discharge in the Indochina Peninsula region were successfully projected using flow routing model 1K-FRM with GCM outputs. The potential changes in river discharge in the region under a changing climate were also examined. The increase of flood risk was found in the Irrawaddy River basin (Myanmar) and Red River basin (Vietnam). The risk of droughts tended to increase in the middle part of Mekong River basin (Lao PDR) and in the central and southern part of Vietnam.

In chapter 4, possible hotspot basins in the Indochina Peninsula region where significant changes related to flood and drought under a changing climate were located by performing statistical significance test. Statistical analysis was carried out to examine the statistical significance of river discharge changes in the region. A clear change of river flow was detected and found statistically significant at the Irrawaddy River basin, the Red River basin, some parts of the Salween and the Mekong River basin, and central part of Vietnam.

In chapter 5, river discharge changes in the Indochina Peninsula region were investigated with multi ensemble experiments from MRI-AGCM and MIROC5 datasets. The uncertainties in climate change projection in the region were considered by comparing results from different ensemble simulations. There is a strong agreement between those ensembles on the increase in annual mean discharge and mean of annual maximum daily discharge in the Irrawaddy River basin, and the increase in mean of annual minimum daily discharge in the upper most part of the Salween River basin and the Mekong River basin. A large majority of simulation results show a decrease in annual mean discharge and mean of annual minimum daily discharge in the central part of Vietnam.

In addition, for the uncertainty in river discharge projection, the uncertainty arising from the differences in cumulus convection schemes and spatial resolution is much larger than the uncertainty sourced from changing sea surface temperature patterns.

In chapter 6, land surface process model SiBUC was applied to reproduce runoff generation data and used as reference data to correct biases in MRI-AGCM3.2S runoff generation data. River discharge in two river basins in Kyushu area, Chikugo River basin and Oyodo River basin, were projected using corrected runoff generation data to examine the performance of land surface process model and bias correction method. Runoff generation data in Kyushu area were simulated quite successfully using SiBUC model with reanalysis data. There was also an improvement in river discharge simulation using corrected runoff generation data. However, more works should be done in bias correction of runoff generation data considering their temporal distribution pattern to improve river discharge projection. The spatial and temporal correlation of runoff generation data between neighbour grid-cells should also be considered.